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SCIENCE AND TECHNOLO

JOURNAL
OF THE
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Vol. 5, No. 3

November 1955

The Multi-Stimulus Olfactometer

(See page 167)

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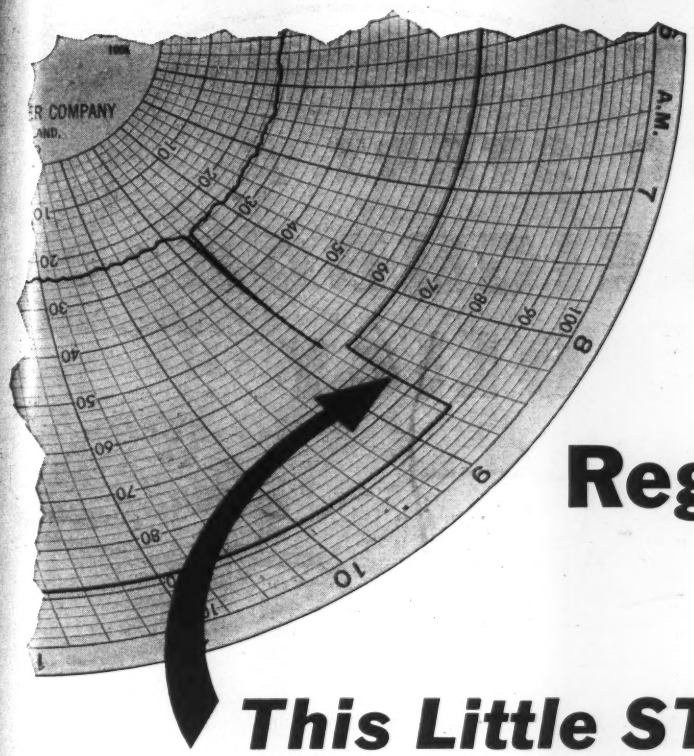

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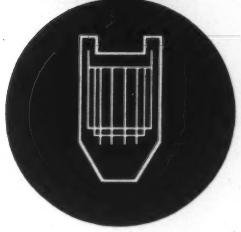

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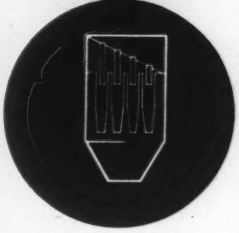

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Formerly "Air Repair"

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The Editor welcomes writers interested in air pollution problems and encourages them to use the pages of this journal for the expression of their opinions. But neither he nor the Association assumes responsibility for the validity of the opinions expressed herein.

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AIR POLLUTION CONTROL ASSOCIATION

4400 FIFTH AVENUE PITTSBURGH 13, PA.

Fellow Members:

I would like to take this opportunity of calling to your attention the culmination, or perhaps more appropriately, the beginning of two projects that have been under consideration for a long time. The first is the publication of the first Technical Coordinating Committee Report on "Continuing Dust Fall Survey". This committee, under the chairmanship of Harlow M. Chapman, has worked diligently to bring out this report and others to follow.

As future issues of the Journal appear, we will present more reports on other subjects. We request that you study them carefully and make such comments as you may see fit. It is only in this way that we can make such reports authoritative in the air pollution control field. I suggest that you read Article XV, Section 4, of the By-laws which appear in the front of your new directory. This will refresh your memory on the procedure followed in making these reports acceptable sources of information.

May I point out that this directory is an up-to-date listing of those in all fields who are drawn together by their interest in this common problem. It is worth your study.

The second project is the appearance of advertising in this issue of the Journal. This is designed to serve a two-fold purpose: first, to provide equipment manufacturers with a medium through which they can reach a select group of prospective consumers; and secondly, to familiarize readers with the application of equipment to air pollution problems. The Publications Committee, under the chairmanship of Henry Aldrich, has had the question of advertising under study for over two years. Many obstacles have been overcome in making it a reality.

We are gradually coming to realize the fruits of the past several years' efforts. More evidence of the work of the staff and our numerous committees will appear in the near future. We hope you will find them worthwhile.

H. K. Kugel

H. K. Kugel
President

Electrostatic Precipitator Studies for Open-Hearth Gas Cleanings*

R. G. THOMPSON, T. L. MYRON, and C. J. DAVIS
U. S. Steel Corporation

The cleaning of the combustible exhaust gases from the steel industry's giant blast furnaces, which convert iron ore into iron, is a well-established art developed over decades, and currently being practiced on a huge scale. Considerably less well understood, on the other hand, is the cleaning of the gas from the open-hearth furnaces, which refine into steel most of the product iron from the blast furnace. This seeming paradox is probably the result of several factors. In the first place, the combustible blast-furnace exhaust gas must be relatively clean to be burned in the regenerative-type stoves that have been used for many years to preheat the air blast for the furnace. In addition, the quantity of valuable iron-bearing dust carried off in blast-furnace gas is such that its removal and return to the furnace constitutes an important operating economy. Open-hearth exhaust gases, on the other hand, contain no heating value, and do not contain sufficient dust to make its removal, and the recovery of the contained metallics, economically attractive.

With the increasing emphasis on the abatement of atmospheric pollution, however, the cleaning of open-hearth stack gas has now become a subject for intensive studies. Inasmuch as the operation offers no direct return on the investment, the installation and operating costs of any technically promising methods are of paramount importance.

Although open-hearth exhaust gases are actually being treated currently with electrostatic precipitators at 3 steel plants in this country[1, 2], basic information concerning the cleaning operation has been lacking. Accordingly, the operation of a pilot gas-cleaning plant was undertaken, (1) to determine the optimum operating conditions for electrostatic cleaning of open-hearth gas under various plant situations, and (2) to provide general information for the design of future facilities, including scale-up factors relating the performance of small test precipitators to that of full-scale units. Because the cost of installing and operating present-design precipitators on many open-hearth installations might be prohibitive, special emphasis was placed on determining how to reduce the required size, and hence the cost, if possible, of the precipitators for a given cleaning job. Other possible methods of cleaning open-hearth gas are also being investigated.

(1) "Precipitators Pass Smoke-Control Tests," *Steel*, 133, 78+ (Aug. 31, 1953).

(2) "Precipitator Installation at Kaiser—Maximum Efficiency Attained," *Steel Equipment & Maintenance News*, p. 24 (Sept., 1954).

*Presented at the 48th Annual Meeting of the Air Pollution Control Association at Detroit, Michigan, May 22-26, 1955

The Open-Hearth Process

A brief description of the open-hearth process itself may aid in understanding the gas-cleaning problem and in following the discussion of the gas-cleaning pilot-plant operation. The open-hearth operation is essentially a batch-melting process carried out in a covered rectangular-shaped furnace. The furnace is provided with a hearth in the shape of a large, shallow, rectangular dish into which is charged pig iron and hot metal from the blast furnace, scrap, iron ore, and limestone. The charge is heated and melted at temperatures as high as 3000°F. by the combustion of a fuel such as oil, natural gas, tar, and coke-oven gas, with an excess of preheated air. The hearth is called "open" because the contained charge is open to the sweep of the hot combustion gases across its surface. The high temperatures, coupled with oxidizing ore and the excess of air, bring about the oxidization of part of the carbon and of other elements to be removed from the iron. The limestone fluxes the impurities and holds them in the form of a slag layer. A single batch of steel, which may weigh as much as 300 tons and require anywhere from 7 to 12 hr. to process, is referred to as a "heat."

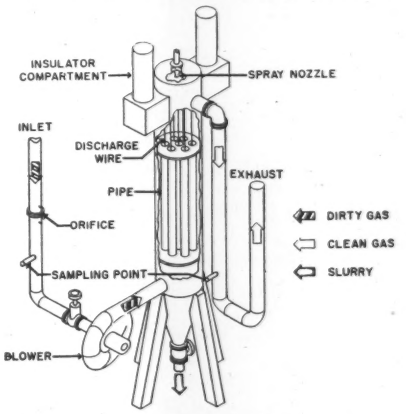

Fig. 1. Schematic Diagram of Experimental Pipe-Type Precipitator

The particulate matter carried by the open-hearth exhaust gas presumably results from the pick-up of fines from the charged material, the agitation and chemical reactions of the molten bath, and the combustion of the fuel. Because the reactions occurring in the bath vary from one period of the open-hearth to the next, the exhaust gas likewise varies considerably with respect to its appearance, composition, dust loading, etc., during the course of a heat. Normal variability in raw materials and in furnace operation, as well as changes in operating practice, also result in considerable variation in the appearance and nature of the exhaust gases. The use of oxygen to "work" the heat is a good example of an operating practice that effects the nature of the exhaust gases. High-purity oxygen, injected below the surface of the slag by means of a lance, is sometimes used to advantage during the "working" or final period of the heat to reduce the total heat time, especially when steel with a very low carbon content is desired. Previous studies indicated that the use of oxygen might pose special cleaning problems.

Thus it can be seen that the variability in the open-hearth process itself results in considerable variability in the properties of stack gases evolved from the process. This naturally complicated the pilot-plant investigation of the gas-cleaning problem, so that it was necessary to conduct a large number of tests to cover the wide range of variables.

The pilot plant investigation included preliminary tests with a small-scale pipe-type precipitator and more comprehensive tests with a large dry-duct precipitator.

Tests With Pipe-Type Precipitator

Fig. 1 is a sketch of the experimental pipe-type precipitator used in conducting small-scale preliminary gas-cleaning tests. The precipitator, which was designed for cleaning 500 ft.^{3} of gas/min., consisted essentially of 7 metal pipes, 4-in. inside diameter and 5 ft. long, mounted vertically in header plates in a cylindrical metal shell. The pipes, which were electrically grounded, served as the

dust-collecting electrodes. The discharge electrodes, which were twisted ¾-in. square rods, hung from the top electrode frame down into the center of each pipe. The gas to be cleaned was drawn from the furnace stack, was passed through an orifice (used for flow measurements), through a blower, and then upward through the 7 collecting electrode pipes.

Precipitator power was obtained from a primary 60-cycle a.c. source of 440 v. After being stepped up to 55,000-60,000 v. by a transformer, the power was transmitted to a mechanical full-wave rectifier that fed unidirectional voltage to the precipitator power cables.

The collected dust was removed from the inside surface of the pipes by intermittent flushing with water, which was introduced through a spray nozzle located in the top of the unit.

The cleaning efficiency of the precipitator was determined by making simultaneous measurements of the dust loadings in the inlet and outlet gas streams, and calculating the per cent of the entering dust that was removed by the precipitator. The equipment used for making the dust-loading determinations and moisture determinations is shown in Fig. 2. The sampling technique consisted of filtering a continuous gas sample through a weighed, porous thimble, and then passing the gas through a condenser, condensate receiver, and gas meter. The grain loading was calculated from the increase in weight of the thimble and the total volume of gas sampled. The moisture content of the gas was calculated from the volume of gas sampled and the sum of the quantity of condensate removed from the gas plus the calculated quantity of moisture in the saturated gas leaving the condenser.

In addition to tests conducted with normal precipitator operation, experiments were also conducted in which various amounts of resistance were added to the pipe-precipitator electrical circuit in the hope of reducing required gas-retention time. Some resistance is normally included in every precipitator circuit to permit the use of higher voltages without the troublesome arcing that might otherwise be encountered. It is theorized that an arc, rather than being sustained, is immediately quenched as a result of the electrical resistance. The use of higher permissible voltages means higher cleaning efficiency at a given gas-retention time, or conversely, a lower required retention time for a given efficiency.

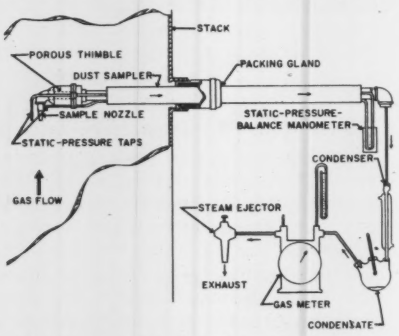

Fig. 2. Apparatus for Measuring Dust and Moisture Content

The summary of test results with the small experimental pipe-type unit is given in Table I. The table represents the results of 20 tests covering all periods of normal open-hearth heats. It can be seen that good cleaning efficiencies were obtained in this experimental equipment at relatively low gas-retention times as compared with those required for similar cleaning in full-scale installations (5 to 10 sec.). As discussed later, the better performance of the experimental unit is primarily the result of the small size and the particular type of unit.

The tests with additional resistance in the electrical circuit indicated that the use of resistance above that normally employed (about 40,000 ohms) would not significantly reduce the required retention time or precipitator size without substantially increasing power costs.

Tests With Dry-Plate-Type Precipitator

The dry-plate-type precipitator was chosen for the larger-scale, more comprehensive study of open-hearth gas-cleaning because a commercial installation of the dry-plate type does not require expensive space-consuming slurry-treatment equipment, such as thickeners, filters, etc., as does a wet-type cleaner. The pilot plant with the dry-plate precipitator was designed for cleaning 3000 scfm. of open-hearth stack gas at about a 2-sec. retention time. As shown schematically in Fig. 3, the gas to be cleaned was drawn from the furnace stack through a run of 24-inch pipe, through the pilot-plant spray tower used for conditioning the gas with moisture, and then through the precipitator. Gas flow through the system was controlled by an automatic valve positioner, which was operated by a flow recorder-controller.

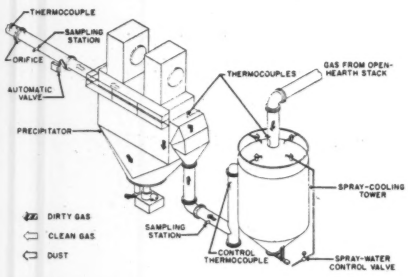

Fig. 3. Pilot Dry-Plate Precipitator Installation

TABLE I
Summary of Test Data With Experimental Pipe-Type Unit

Gas Retention Time, seconds	Flow cu.ft./min.	Average Cleaning Efficiency %
0.88 to 0.58	200 to 300	99 - 98
0.58 to 0.44	300 to 400	98 - 96
0.44 to 0.35	400 to 500	96 - 92

As shown in Fig 4, the spray tower was a double-shelled cylindrical vessel with a conical bottom; the entering gas passed down through the inner shell and up through the annular space between the inner and outer shells to the exit. To determine the effect of gas conditioning on precipitator operation, 4 spray nozzles were used to inject water or steam into the gas during tests. An automatic valve regulated the spray-water flow. During tests without gas conditioning, the spray-tower shell served simply as part of the duct work carrying the gas to the precipitator.

From the spray tower, the gas flowed through a 24-in. duct to a standard dry-plate type of electrostatic precipitator. In the precipitator, a vertical cross section of which is shown in Fig. 5, the entrained dust was collected by electrostatic deposition on expanded-metal collection electrodes. The collection electrodes were rapped continuously by air vibrators to dislodge the collected dust, which then fell into the collecting hopper. A dust plow in the bottom of the hopper moved the dust to the rotary discharge valve for removal from the unit. The clean gas leaving the precipitator passed through an 18-in. main to the exhaust fan for discharge into the atmosphere.

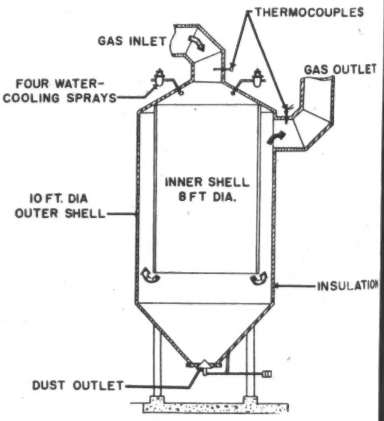

Fig. 4. Spray-Cooling Tower

TABLE II

Summary of Test Data with Dry-Plate Precipitator[a]

	Normal Heats		Oxygen-Worked Heats	
	Unconditioned	Conditioned With Moisture	Unconditioned	Conditioned With Moisture
Moisture Content of Inlet Gas, % by volume	544-623 6 - 8	433-560 14 - 20	566-744 2 - 10	492 - 565 17 - 34
Inlet-Gas Temperature, °F.				
Cleaning Efficiency, %	86 - 97	83 - 95	76 - 91	85 - 91

(a) Average gas-retention time in electrostatic field, approximately 2 seconds

As with the smaller pipe-type installation, precipitator power was obtained from a primary 60-cycle a.c. source at 440 v. After being stepped up to 56,000 v. by a transformer (the highest practical operating voltage for this design of precipitator), the power was transmitted to a mechanical full-wave rectifier that fed unidirectional voltage to the precipitator power cables.

Inlet and outlet dust loadings and moisture contents were determined in the same manner described for the small pipe unit.

The pilot-plant investigation included 125 individual tests, which covered operation at various gas-retention times, operation with and without gas conditioning, and operation during various periods of the open-hearth heat, including oxygen-blowing periods.

Table II, which is a summary of all the pilot-plant data, shows that cooling the gas and increasing its moisture content by water conditioning (which for some gases results in increased cleaning efficiency) did not appreciably affect the efficiency obtained for open-hearth stack gas, either during normal or during oxygen-working periods. Water conditioning or other methods of gas cooling would, nevertheless, be required in an open-hearth installation not equipped with a waste-heat boiler, because of the high gas temperatures that would be encountered. It can be seen that the gas temperature measured at the inlet of the precipitator, even when gas was not water-conditioned, was relatively low (as compared to the stack temperatures of 1000° to 1500°F.). This resulted from the passage of the gas through the long run of pipe between the open-hearth stack and the pilot plant. Because of this cooling, the pilot plant was, in effect, cleaning gas from an open hearth installation equipped with a waste-heat boiler.

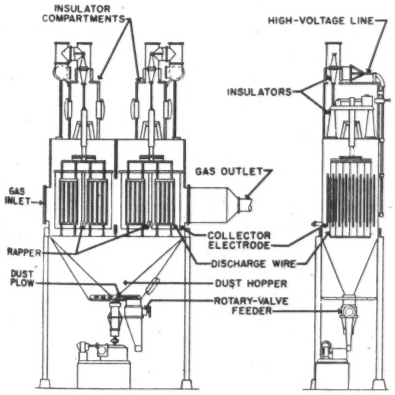

Fig. 5. Dry-Plate Precipitator

Table II also shows that when oxygen was used to work the heat, cleaning efficiencies were lower than those obtained during normal operation. This would indicate the need for somewhat larger cleaning installations at the many open-hearth shops where oxygen is used, if comparable results are contemplated.

The results of the tests are also summarized in Fig. 6 in the form of a plot of the standard equation[3] for electrostatic precipitation. This equation, which correlates cleaning efficiency with gas-retention time far a particular precipitator and particular test conditions, is

$$\text{Log } (1-E) = (\text{Log } K)\, t$$

Where E = cleaning efficiency expressed decimally
t = gas-retention time in seconds
K = precipitator constant for a given precipitator

The curve of this equation is a straight line that intersects zero retention time at $(1-E) = 1$ on a semilog plot of $(1-E)$ *vs.* t. It can be seen that the points for normal heats (each point being an average of about 25 tests) fall close to such a theoretical straight line.

Because, for normal heats, the observed relationship of efficiency vs. retention time is in good agreement with the theoretical relationship, the tests on oxygen-worked heats were limited to one retention time, on the assumption that the efficiency for any other retention time could be obtained from the theoretical straight line. The point shown for oxygen-worked heats is the average of 9 points determined at about 2 sec. retention time. The graph shows that at a given retention time, a lower efficiency can be expected with oxygen-worked heats; or conversely, to obtain a given efficiency, a longer retention time, and hence a larger unit, is required for cleaning the gas from oxygen-worked heats.

(3) Perry, John Howard, "*Chemical Engineer's Handbook*," 2nd Ed., p. 1869, McGraw-Hill, New York, N. Y., 1941.

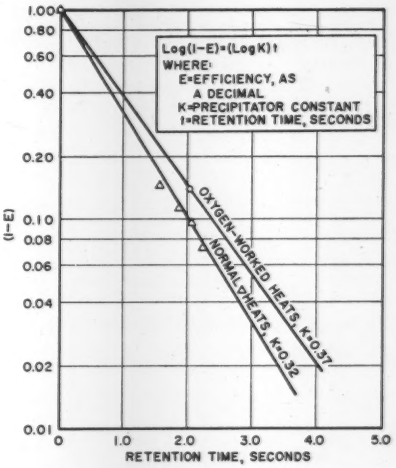

Fig. 6. Determination of Precipitator Constant for Open-Hearth Stack Gas

The K values calculated from the plots (0.32 for normal heats and 0.37 for oxygen-worked heats) fall in the normal range of values reported for precipitator installations[3]. It should be mentioned, however, that the K values obtained in this investigation give the relationship between efficiency and retention time for this particular precipitator. In designing a full-scale installation, the precipitator manufacturer would correct these values on the basis of the scale-up factor and the differences in design details between the pilot unit and the particular full-scale unit.

The average dust loading of the open-hearth stack gas for the various periods of all the heats studied was 0.2 gr./scf. The maximum loadings occurred during the hot-metal addition, during the ore and lime boils, and during periods when oxygen was used to work the heat.

The collected dust could be easily wetted with water to make a mixture that could be handled.

It is interesting to note that the corresponding gas-retention times are significantly higher for the large dry-plate unit than for the small pipe-type unit tested (2 sec. as compared to 0.5 sec.), the difference being the result of several factors:

1. The pipe-type unit is inherently more efficient than the dry-plate unit because the centrally positioned discharge electrode in a pipe unit is equidis-

(continued on page 182)

The Long-Range Effect of Industrial Air Pollution on the Purity of Air Masses Nation-Wide. Is the Mass Self-Cleaning?*

Leslie A. Chambers
Robert A. Taft Sanitary Engineering Center
U. S. Public Health Service
Cincinnati, Ohio

The concept of self-purification has acquired a special connotation among those who have been concerned with problems of stream pollution and the purity of water supplies. Perhaps it is for this reason that the Chairman of the Program Committee suggested the title for this paper. In his initial letter to me, he commented that the answer to the question posed was obviously "yes." Probably no one would disagree with this categorical answer, and yet there are reasons why the mechanisms for dissipation, transformation and removal of foreign substances from the air mass are fruitful subjects for consideration at the present time.

In spite of the apparent infinity of the space around us, and the vigorous and frequent wet scrubbing action of rainstorms in the lower air levels, there is abundant evidence that pollutants from both natural and artificial sources persist in the air mass for very long periods of time. The effects of volcanic dust from the explosion of Krakatoa were measurable, in terms of light scattering, for many years. Clouds of smoke from western forest fires have affected the quality of sunlight reaching eastern coastal cities for weeks, and dust from wind erosion of the central plains has remained measurable for months over much of the northern hemisphere.

Since 1946, there have been numerous opportunities to follow the dispersal of man-made pollutants tagged with radioactivity. Each detonation of a nuclear weapon has resulted in the spread of radioactive by-products through the air mass in a manner which must be similar to that of the distribution of other, less easily followed pollutants. Outside the immediate zone affected by the bombs, the amount of radioactivity has never been large enough to be acutely hazardous. But the rise and decline of radioactivity in the atmosphere certainly parallel the build up and slow disappearance of the particles with which the activity is associated. The effects of a bomb test can be detected for many months. Almost certainly, detailed study of the patterns of radioactivity in the air mass as a function of time will provide a basis for estimating the rate at which cleansing processes affect other air pollutants.

Air Streams

In any consideration of the problems related to air pollution by those who have been concerned with surface waters, the strong analogies between the two problems are striking. In both cases we are dealing with masses of substance having structures which have considerable similarity. An air mass is bounded in general by an inversion layer which corresponds roughly to the surface of a stream. Beneath this inversion layer there are exhibited flow patterns that are closely analogous with those of large streams. The direction of flow may vary from time to time, depending on the direction of temperature gradient, and this factor, of course, complicates theoretical considerations. The body of air also exhibits stratification due to temperature gradients and at times is extremely turbulent, resulting in vertical and horizontal mixing within the general mass. Of course, there is constant diffusion and flow out of a local area into the more extensive continental and world-wide air masses, but at some level we can define meteorological boundaries, which though evasive, lead us to finite dimensions for the body of substance with which we are dealing.

It must also be remembered that the flow of the air stream can, at times, cease completely, just as the flow of a stream of water can drop to a minimum. At such points in the aerodynamic or hydrodynamic sequence of events, pollutants introduced into the mass cease to be influenced by movement, and concentrations can be built up, due to stagnation. This has happened repeatedly over most metropolitan areas, and in some few cases has resulted in such great concentrations of foreign materials locally that people, plants, and animals have been killed. The condition represents the minimum flow situation on which estimates of the capacity of a stream of water to accommodate wastes is usually based. Similarly, it will probably be regarded in the future as the condition which determines the capacity of the air over a city to assimilate airborne wastes.

But we are not presently considering the local accumulations of pollutants. Rather, we are exploring the effect of multiple local loadings on the final quality of the air mass of the continent or the world. For the past two years, the Public Health Service has had in operation a sampling network, involving approximately 30 metropolitan areas and an equal number of suburban and rural areas in the United States and Alaska. While one purpose of this continuous measurement of particulate material has been the comparison of local metropolitan airloadings, another result has been the determination of the minimal, continuous particulate concentration of air distributed over the United States. Thus, we have a reasonable estimate of the aerosolized pollution load of the air mass into which any new foreign substances must be introduced.

The evidence is that at all times our air, at a few feet above ground level, has a basic concentration of approximately 50 micrograms of particles per cubic meter. For what it is worth, this can be converted into actual tonnage distributed through the air mass over the continental United States. There is, at practically all times, an inversion lid at 5,000 to 8,000 ft. above the surface; so if we assume a land area of 3,000,000 mi.^{2}, it can be calculated that we are dealing with an air mass of approximately 3,000,000 mi.^{3} Uniform distribu-

*Presented at the Industrial Section of the Texas Water and Sewage Works Association's Short School, March 7-9, 1955.

tion of 50 $\mu g./m.^3$ would mean that at any given moment there are approximately 500,000 tons of particulates hanging in the air all of us use. Reference will be made to this extremely hypothetical figure later on in the discussion.

The analogy with water pollution problems can be carried considerably farther when we look at the factors which participate in the removal or transformation of foreign substances from water or from air. Naturally, any particles large enough to be affected by gravity more than they are affected by thermal actions, winds, or water flow, will settle to the bottom. Thus, a large factor in the elimination of heavy particles from either water or atmosphere is sedimentation.

Furthermore, in the case of both water and air, there are concentrations of particles, of a given size, above which there appears a tendency of the particles to aggregate, increase in weight and, therefore, fall out. This tends to establish an upper limit for particulate loadings with respects to particles of definite size classes.

Again, a variety of forces leading to dilution of the pollutants are operative in both air and water. These include turbulence, and natural diffusional tendencies of the particle through the respective media. Particles of small size are so greatly affected by these dispersive forces that they may, in fact, never be influenced significantly by gravity. Dispersion or dilution, of course, does not remove substances from the air mass, but rather, takes advantage of the enormous volume to maintain low levels over a long period.

The analogy between air-pollution problems and water pollution can be carried still further, if we consider chemical interactions which take place in either medium when proper combinations of reactants are present in appropriate concentrations. I suppose in a very strict sense, chemical interactions cannot be regarded as self-purifying phenomena, since they result in a change of chemical form of substances, rather than in a reduction of their concentration. However, photochemical processes and simple chemical interactions have been so strongly advanced in explanation of both the abatement and the production of undesirable substances that they cannot be ignored. Furthermore, photochemical processes involving the intermediation of algae and other chlorophyll-containing organisms are a major factor in the stream pollution picture. Probably it is only in the realm of biological cleansing reactions that the analogy between air and water breaks down. So far as is known, biological processes do not contribute substantially to removal of substances from air or to their chemical transformation except insofar as they are involved in the oxygen-CO_2 cycle.

Under the Lid

Reference has been made to the continental air mass. Some of its characteristics are recognizable. There exists an inversion lid which is fairly general over the entire continent. Anyone who has flown extensively, especially over the mid-continent area, will have observed the existence of the so-called dust horizon about a mile off the ground. When viewed at a sharp angle, it is so noticeable as to appear almost solid even in the total absence of clouds, and especially during the summer months. Below this lid there are the easily observable thermal movements which we recognize as breezes, winds, and cyclonic disturbances of low order. Also beneath the lid there are recognizable, although variable and transient streams of air which flow characteristically in one direction or another, depending on the generation of thermal gradients. Strata of different air densities form from time to time, constituting a series of lids under lids just as in the case of a stream.

There is within this air mass a constant tendency toward flow both north and south, the effect of the polar air mass being to push southward, while the band of tropical air around and above the Equator tends to push the cold air northward. A constant stirring of the mass is, therefore, produced by this action, as well as by the normal west to east progression of the air mass counter to the rotation of the earth, and by the vertical inroads of the circumpolar jet stream several miles aloft.

At times, of course, the disturbances aloft and the thermal gradients generated by absorption of heat at the ground level result in massive breakthroughs of the inversion lid, as in the case of the usual type of thunderstorms, or the formation of stratocumulus clouds. How much loss of accumulated pollutants from below the mile-high inversion layer can be accounted for by these frequent breaks through the lid is not known, but is probably large.

This, then, is the mass of air into which we now dump the gaseous, vaporized, and aerosolized wastes of agriculture, industry, transportation, and our households. We have approximately 3,000,000 $mi.^3$ of air with which to play if we consider only that of the United States, but it is probably fairer to consider the volume of air covering the entire earth.

In all of past history, up to and including the present time, the amount of airborne material produced by forces of nature from natural sources has been tremendously greater than that produced by the feeble activity of man. Only within the past 20 years have concentrations of pollutants over the cities of the world become of such frequent occurrence as to create any general public interest. The amount of dust, fumes and vapors contributed annually by windstorms, volcanic action, vegetation cycles, and other things outside the control of man can be reckoned in terms of billions of tons annually. The cleansing forces at work in the atmosphere have been able to cope with this contribution and to maintain an air supply which, apparently, as indicated above, contains no more than about one-sixth of a ton of solids/$mi.^3$

On the other hand, where populations have increased, the amount of particulate matter, both organic and inorganic, now far exceeds this value. For example, some recent samples from the City of London, showed a concentration of almost 3,000 $\mu g./m^3$, as compared with 50 for the rural background. In the air over a representative group of American cities, the time-integrated loading of the air for a period of more than a year has exceeded 250 $\mu g./m.^3$, continuously. Perhaps 90% of the particles are so small as to be permanently suspended in the air unless washed out by rainfall or caused to aggregate by some means. Thus, they can be expected to contribute to the general background of air pollution over the continent or the world.

It is also evident from these studies that the amount of finely divided materials arising locally is fairly closely associated with density of population. At the present time we have approximately 162,000,000 people in the United States. 51% of these are said to live in metropolitan areas, representing 1.5% of the total land area. Recent figures released by the National Office of Vital Statistics predict a population of 221,000,000 by 1975. This growth of population will presumably involve development of high population densities over a substantially larger fraction of the continental area. It can be inferred that, barring effective change in our habits, both industrial and domestic, there will be a commensurate increase in the load of effluents the air mass is called upon to accommodate.

Our problem is clearly one which though not acute at present, is related to the national development and can be expected to increase in acuity with passing years. It is only after man has become a sufficiently dominant form of matter on

(continued on page 184)

Air Pollution Damage to Vegetation*

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The problem of gas damage to vegetation has become increasingly significant in recent years with the continued expansion of industry and growth of population. The principal agents of air-pollution damage of economic importance are probably sulfur dioxide, fluorine compounds, and "smog gases" of the type encountered in the Los Angeles area. Other gases may be of concern in special cases but their effects are usually limited to the immediate neighborhood of the source. Sulfur dioxide damage to plant life and its mode of action have been studied extensively for many years. The literature in this subject has been reviewed by Katz[6], Thomas [18] and others [19, 22].

Widespread effects of fluorine compounds on vegetation in recent years have coincided with the growth of the aluminum and steel industries, although this type of damage was known earlier in Europe near operations associated with the manufacture of superphosphate fertilizer, bricks, ceramics, and pottery. Lesions on crop plants and trees, relative susceptibility, and other aspects have been discussed by Miller[12], Thomas[18], Daines[3], and Zimmerman[22, 23].

Smog gas injury has been reported in the Los Angeles district on a large scale, affecting many species of leafy vegetables and other crops, particularly endive, spinach, and Romaine lettuce. The damage symptoms can be reproduced by the action of gasoline vapors and ozone, or by the photochemical oxidation products of gasoline hydrocarbons and nitrogen dioxide. The greatest injury was produced by n-hexene and n-pentene in the presence of the above "oxidants".[4, 10].

Phytotoxicity and Anatomical Effects

The toxicity of sulphur dioxide, hydrogen fluoride or volatile fluorine compounds, and "smog gases" vary considerably, depending upon water solubility, rate of absorption and degree of reactivity with the leaf tissues, effect on the pH of the plant buffer system, oxidation or reduction reactions with plant components, and inherent toxicity of the element or compound[18]. Sulfur dioxide is readily absorbed by plants but it is not a systemic poison. In low concentrations (below about 0.3 ppm.) the gas is oxidized to sulphate in the plant at about the same rate as it is absorbed. There is no injurious effect from this accumulation of sulphate in the leaves, which may reach a level considerably higher than in unexposed plants, until the threshold value for sulphate is exceeded[6,19] High concentrations of this gas result in the rapid accumulation of sulfurous acid or sulfite in the interior leaf cells; and this may cause a toxic action, such as plasmolysis, inhibition of photosynthesis of a temporary or more permanent nature, or injury to the chloroplasts and enzyme system with resultant degradation of the chlorophyll pigments[5,18].

Gaseous fluorine compounds are much more toxic to many species of vegetation than equivalent concentrations of sulfur dioxide. The fluorine accumulates in the leaves and other parts of the plant during the growing season even at atmospheric concentration levels lower than 0.01 ppm. by volume. The greatest accumulation usually occurs at the tips or margins of the leaves, and if lesions appear, they are generally noted first at these extremities. However, the tolerance limit for fluorine varies widely in different plant species. Gladiolus may be injured by absorption of as little as 20 to 30 ppm. of fluorine by weight of dry leaf tissue. Apricot, peach, prune, and some conifers are also very susceptible to injury from fluorine accumulation. Other species, such as cotton, bean, spinach, and forage crops are much more resistant to fluorine accumulation[3, 18]. Thomas has reported that cotton leaves may absorb as much as 5,000 ppm. (dry basis) without injury[18]. Probably the most serious aspect of fluorine absorption is the fluorosis in animals which is developed by feeding on forage and pasture contaminated by atmospheric fluorides.

An excellent review of the various types of symptoms or lesions resulting from fluoride injury to plants has been presented by Thomas[18]. In appearance there are many points of similarity with sulfur dioxide markings, although the fluorine discolorations show a different distribution as to location of the injury and occur frequently at the tips and margins of the leaves, or in spots. In both sulfur dioxide and fluorine markings there are acute and chlorotic types. In the early stages of injury there is evident plasmolysis of the affected cells, resulting in areas of water-soaked tissue which may dry out rapidly. The toxic effects of fluorine involve inhibition of photosynthesis (which may be permanent) and inactivation of enzyme systems such as phosphatase, enolase, and amylase. However, unless the source of pollution is known, or varietal differences in susceptibility are sufficiently pronounced, the diagnosis of gross symptoms in the field must be confirmed by chemical analysis of the vegetation before a positive decision can be made between fluorine and sulfur dioxide as the casual agent.

Bobrov [1] has described the anatomical effects of smog damage to plants as noted in the Los Angeles area. Her microscopic studies indicate that the reaction of the plant cell to hydrocarbon-ozone products is the same in all susceptible plants, regardless of the gross damage picture. The first visible response, whether in the field or in the laboratory, is a shiny, water-logged appearance on the under surface of the leaf. The epidermal cells, as well as affected guard cells of the stomata, swell and become turgid or filled with water. Chronic and

(3) Daines, R. H., Leone, I., and Brennan, E. Chapt. 9, "U. S. Tech. Conference on Air Polution", McGraw-Hill, New York, 1952.

(6) Katz, M., *Ind. Eng. Chem.*, **41**, 2450 (1949).

(12) Miller, V. L., et al., Chapt. 11, "U. S. Tech. Conference on Air Pollution," McGraw-Hill, New York, 1952.

(18) Thomas, M. D., in "Annual Review Plant Physiol," **2**, 293 (1951).

(19) Thomas, M. D., Hendricks, R. H. and Hill., Geo. R., *Ind. Eng. Chem.*, *42*, 2231 (1950).

(22) Zimmerman, P. W., *Proc. First National Air Pollution Symposium*, Stanford Res. Inst., **135** (1949).

(23) Zimmerman, P. W., Chapter 13, "U. S. Tech. Conference on Air Pollution," McGraw-Hill, New York, 1952.

* Presented at the 48th Annual Meeting of the Air Pollution Control Association at Detroit, Michigan, May 22-26, 1955.

(4) Haagen-Smit, A. J., et al., *Plant Physiol.*, **27**, 18 (1952).

(5) Katz, M., Ledingham, G. A., McCallum, A. W., et al., "Effect of Sulfur Dioxide on Vegetation," National Research Council of Canada, No. **815**, pp. 447, Ottawa, 1939.

(10) Los Angeles County Air Pollution Control District, Annual Reports,, 1948-51, Los Angeles, Calif.

(1) Bobrov, A., *Proc. Second National Air Pollution Symposium*, Stanford Res. Inst., **129** (1952).

acute damage to the leaf tissues will depend upon the extent of this plasmolysis and the length of time that the cells remain in this state. If the period is short, the cells may recover their normal functions. The "silver leaf" appearance of many species is due to the entrapment of air in the intercellular spaces of the leaf as the affected cells die by dehydration. Gross damage symptoms from such "smog gases" have been described in detail recently by Stanford Research Institute[16]. Here again, the order of susceptibility of plant species differs from that of either sulfur dioxide or fluorine.

Katz, Ledingham and McCallum[5] have described in considerable detail the great variety of gross symptoms of sulfur dioxide injury on forest and crop plants. In net-veined dicotyledonous plants, such as alfalfa, the acute markings, resulting in actual killing of the cells, may be classified as (a) marginal, (b) concentrated intercostal, (c) diffuse intercostal, and (d) veinal. Diffuse intercostal markings were characterized by a lack of definition of the borders of injured areas. These areas spread across the veins as the chloroplast cells are destroyed, although the midrib is usually quite free from injury. Such markings are more often found on the lower shaded leaves of the plant under gas fumigation conditions of low light intensity and high humidity. Frequently the diffuse type of marking affects only one side of the leaf. Under conditions of low light intensity, sulfur dioxide markings may follow the veins, with the intervening areas and the midrib comparatively free from injury. Acute injury to monocotyledonous plants, where the leaves are parallel-veined, may take the following forms: (a) the tip-burn or "kill back" type, which may affect the tip of the leaf or a larger portion back from the tip; (b) the mottled or spotted type; and (c) the banded type. There is also a type of marking which imparts a dull gray-green color when the epidermal cells on only one side of the leaf are killed.

Cholorotic injury is the result of a breakdown of the chlorophyll in the leaf and may be either a temporary or permanent condition. The leaf tissue may still exercise its functions, but at a reduced rate. In the transient form, the chlorosis consists of a slight paling of the normal green color which is usually restored within a few days. Where the chlorosis is of the permanent type, the loss in chlorophyll content is evident in the yellow or yellowish-green appearance of the leaves. The gross symptoms of permanent chlorosis are similar in appearance to senescence and may result from the continued absorption of gas and its accumulation as sulfate in the leaf beyond the tolerance limit.

The gross symptoms of acute injury of the affected leaf tissue are merely the post-mortem appearance. Anatomical effects observed under the microscope in the initial stages of injury are the appearance of water-soaked, flaccid areas of diffuse greyish-green coloration or plasmolysis of affected cells. The chlorophyll appears to diffuse from the chloroplasts into the rest of the cytoplasm in the cells. However, at this stage, the plastids still retain their shape, very little shrinkage of the vacuole has taken place, and the protoplasm lining the cell wall is apparently still unaffected. The greyish-green color will persist for some time, if the leaf is protected from light. In the presence of sunlight, there is rapid desiccation of the affected area, accompanied by a great shrinkage of the cell contents. The leaf chlorophyll and other green pigments are decomposed, and the leaf assumes a bleached, reddish-brown, brown, or ivory appearance, depending upon the nature of the species.

Effect on Chlorophyll

It is apparent from the foregoing discussion that sulfur dioxide, fluorine compounds, and smog in common cause (a) plasmolysis of the affected tissue and (b) inhibition of photosynthesis or degradation of chlorophyll. It is inconceivable that an adverse effect on the photosynthetic process should not be accompanied by some change in the chloroplasts or in enzyme systems associated with chlorophyll activity. With acid gases or vapors, the initial action on the chlorophyll pigments is conversion to the corresponding pheophytins. In the case of oxidation products of the C_5 to C_9 aliphatic hydrocarbons (smog gases), the cholorphyll may be oxidized irreversibly to complex decomposition products of unknown composition. The extent of decomposition of chlorophyll or conversion to pheophytin is a measure of the degree of air-pollution damage to leaves of plants, and this can be determined readily by spectrochemical methods. This procedure is especially useful in cases where the leaves or portions of them are not affected by acute symptoms, and it is necessary to determine whether such tissue is fully functional or otherwise.

The classical investigations of Willstatter and Stoll[21] showed that when chlorophyll is treated with dilute acids there is formed a derivative, pheophytin, by quantitative replacement of the magnesium atom of the chlorophyll nucleus with hydrogen. Molisch[13] found pheophytin to be present in gas-damaged leaves. Subsequently, Roben and Dorries in 1932[14] described experiments on the effect of sulfurous acid on Elodea canadensis in which the formation of pheophytin from chlorophyll was noted in shorter exposure periods, followed by bleaching of the green pigment and subsequent disappearance of the pheophytin as well, with time or at higher acid concentrations. It was also noted that sulfuric acid was far less damaging to the plant than sulfurous acid at equivalent hydrogen-iron concentration.

It has been suggested that pheophytin may be formed naturally during the autumnal yellowing or senescence of plants by organic acids released in the leaves in contact with the chlorophyll, as a result of the disintegration of plasma proteins[20].

Extraction of Green Pigments from Conifer Leaves

In order to determine the effect of air pollution exposure and damage on the chlorophyll and pheophytin content of living plants, conifers were selected as the most suitable species for study purposes. A number of collections were analyzed from pine and spruce trees growing in the Detroit River industrial and residential-rural areas where the pollution consists of the combustion products of fuels (mainly solid fuel), acid gases (preponderantly sulfur dioxide), and aerosols of varied composition. The nature of this pollution has been described elsewhere [8, 15]. Other samples of conifer leaves (white pine) were taken from the Sudbury, Ont., nickel-copper smelting district where the major contaminant is sulfur dioxide. The green pigment content of normal, healthy specimens was determined from collections in natural forest and rural areas of Ontario. The collections were made in the fall of the year and only the current year's needle growth was analyzed.

The method of extracting the chlorophyll and other pigments from the fresh plant tissue was essentially the procedure

[5] See footnote 5, page 144

[16] Stanford Research Institute, Report on The Smog Problem in Los Angeles County, January 1954.

[21] Willstatter, R., and Stoll, A., "Untersuchungen uber Chlorophyll," Julius Springer, Berlin, 1913.

[8] Katz, M. Proc. *Second National Air Pollution Symposium*, Stanford Res. Inst., **95**, (1952).

[13] Molisch, H., "Mikrochemie der Pflanze," 3 Auft., Gustav Fischer, Jena, 1923.

[14] Roben, M., and Dorries, W., *Berichte der Deutschen Botanischen Gesellschaft*, **50**, 53 (1932); Dorries, W., *Ibid.*, **50**, 47 (1932).

[15] Shore, Violet, and Katz, M., *Am. Ind. Hygiene Assoc., Quarterly*, **15**, 297 (1954).

[20] Wieler, A., *Jahrbuch fur wiss. Botanik*, **84**, 764 (1937).

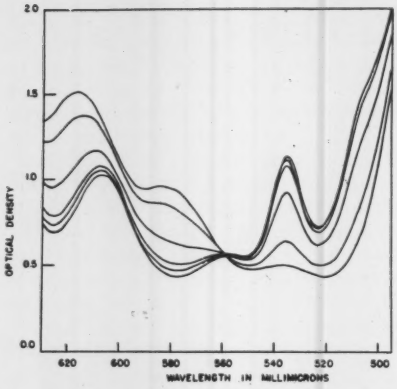

Fig. 1. The Acid Conversion of Chlorophyll to Pheophytin Measured at Various Time Intervals over a Period of 4 hr., Indicating the Isosbestic Point at 560 mμ.

recommended by Comar and Zscheile[2]. In each specimen of conifer leaves, the new needle growth was separated from the previous year's and cut into pieces about 0.5 cm. long with scissors. A weighed sample of this was then extracted in a mortar with 90% aqueous acetone, to which a little calcium carbonate had been added. The plant extract was filtered by suction and the residue ground with more acetone. This process was repeated until the tissue was devoid of green colour and the plant extract was made up to a definite volume with 90% aqueous acetone. This whole operation was carried out as rapidly as possible to avoid degradation of the plant pigment.

Another weighed sample of the same needles was dried in a 70°C. oven for 24 hr. in order to determine the moisture content.

The measurements of light absorption of the extracts in 1953 were made on a Beckman D. U. spectrophotometer, but

(2) Comar, C. L., and Zscheile, F. P., *Plant Physiol.* **17**, 198 (1942).

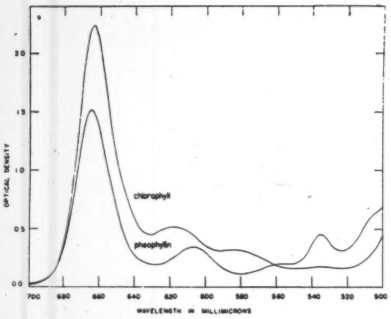

Fig. 2. Absorption Spectra of Chlorophyll and Pheophytin, Concentration 7.7 mg./l.

in later work a Cary automatic recording spectrophotometer was used.

Calculation of Results

Twelve standard extracts were prepared from healthy conifer specimens collected locally and extracted within 15 min. of collection. Two aliquots of each were made up to volume with 90% aqueous acetone, and 90% aqueous acetone containing a little oxalic acid, respectively. The acid converts the chlorophyll to pheophytin at a rate which is dependent upon the normality of the acid. The absorption of the solution was measured at various time intervals until the reaction was complete (Fig. 1).

It was apparent as noted by Mackinney[11] that the chlorophyll and pheophytin absorption curves crossed in the neighborhood of 560 mμ. Thus, the absorption at this wavelength is independent of the amount of conversion to pheophytin and may be used to calculate the concentration of chlorophyll plus pheophytin in the plant extract. (See also Figs. 2 and 3).

Based on a specific extinction coefficient of 5.2 at 560 mμ., the absorbancy indices for chlorophyll (a+b) and pheophytin (a + b) at 535 mμ were

(11) Mackinney, G., and Weast, C. A., *Ind. Eng. Chem.*, **32**, 392 (1940).

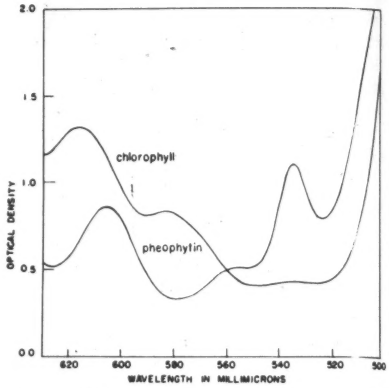

Fig. 3. Absorption Spectra of Chlorophyll and Pheophytin, Concentration 19.2 mg./l.

calculated as 4.3 and 11.0 respectively. These values could then be used to determine the concentration of chlorophyll plus pheophytin and the percentage conversion to pheophytin. Since both pheophytin *a* and *b* contribute to the peak at 535 mu [11, 21], no serious error is introduced by regarding the pheophytin as a single component in this region.

The concentration of chlorophyll + pheophytin is given by

$$C_1 = \frac{560\ D}{K_1\ d}$$

where D=optical density
d=cell length
K_1=specific extinction coefficient at 560 mμ

C_1=concentration in gm./l

The percentage conversion to pheophytin in the unknown mixture is calculated from the equation

$$\frac{\frac{535\ D}{d} - C_1K_2}{C_1K_3 - C_1K_2} \times 100$$

where K_2 and K_3 are the specific extinction coefficients at 535mμ for chlorophyll and pheophytin respectively.

Effect of Storage and Drying

Since all samples were shipped to the laboratory in sealed containers, analyses of white pine leaves were made at inter-

(21) See footnote 21, page 145

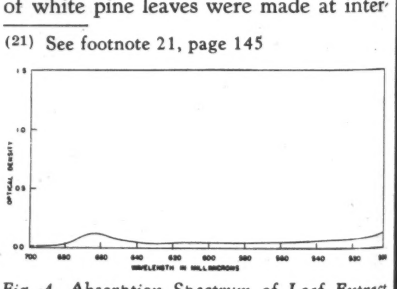

Fig. 4. Absorption Spectrum of Leaf Extract from Browned Portion of White Pine Needles Injured by Sulphur Dioxide

TABLE I
Effect of Drying White Pine Leaves at Room Temperature

Storage Period, days	Green Pigment mg./gm., dry basis	Moisture Content %	Conversion to Pheophytin, %	Chlorophyll (*a* + *b*), mg./gm., dry basis
1	4.3	59.5	6.1	4.0
2	4.0	56.3	5.2	3.8
4	4.6	54.3	3.4	4.4
6	4.0	38.7	10.0	3.6
10	4.3	9.5	47.2	2.3
17	4.6	7.9	53.0	2.2
22	4.7	7.3	48.7	2.4
Effect of Freezing and Thawing				
1	4.5	61.3	4.1	4.3
5	4.4	59.0	27.0	3.2
13	4.8	57.7	49.5	2.4

vals over a period of 22 days in order to determine the effect of storage or air drying at room temperature on the pheophytin content. The results are shown in Table I. It was apparent that after 6 days the water content decreased very rapidly and the pheophytin content increased proportionally. Storage at freezing temperatures was also tested in this manner and, although under these conditions the water content remained high, the pheophytin content increased just as rapidly as before. Apparently, enzymatic changes in the leaf tissue resulted in the release of organic acids with conversion of the chlorophyll to pheophytin.

The earlier specimens of 1954 needle growth from the Sudbury district had dried out somewhat in transit, even though the leaves were sealed in tins, and the variations in water content made it difficult to assess the analyses. This work did show, however, that sulphur dioxide injury caused a more rapid drying out of the leaf tissue than was apparent with healthy specimens. Two samples of similar age collected in the same locality at the same time gave the following results. Pheophytin conversion: healthy sample, 4.7%; SO_2 injured sample, 17.7%. Water content: healthy sample, 49%; SO_2 injured sample, 10.3%.

Later samples were enclosed in aluminum foil, before placing in sealed containers, and this procedure kept the specimens in good condition. The samples were analyzed in the laboratory within 1 to 3 days after collection in the field.

An analysis of the browned portions of injured needles showed that these contained no pigment extractable with aqueous acetone (Fig. 4). For this reason, only the green or chlorotic portions of badly discolored needles were analyzed. Brown tips of needles were clipped off and discarded.

Chlorophyll in Normal Conifer Leaves

The chlorophyll, moisture, and pheophytin conversions in healthy specimens of white pine needles are indicated in Table II for 9 collections made in the late fall of 1954 in natural forests and rural areas of Ontario. The range of pheophytin conversion is from 0.0 to 2.0%. Although great care was exercised in preserving the samples in their natural state prior to analysis, and in preventing any transformation to pheophytin during extraction with solvent, traces may have been formed. It is apparent, however, from Table II, that there is little if any pheophytin present in normal conifer leaves that do not show symptoms of senescence or discolorations from other causes. The mean chlorophyll content is 3.7 mg./gm. (dry basis) and the mean pheophytin conversion is only about 1%.

TABLE II

Chlorophyll and Pheophytin Conversion in Normal White Pine Leaves

Current (1954) Needle Growth

Location	Green Pigment, mg./gm., dry basis	Moisture Content, %	Conversion to Pheophytin, %	Chlorophyll ($a + b$), mg./gm., dry basis
Victoria	3.5	45.5	2.0	3.4
Algoma	4.5	45.5	1.2	4.5
Kirkwood Forest Reserve	3.6	50.3	0.4	3.6
Mattawa	3.7	59.1	1.8	3.6
Mattawa	3.9	62.8	0.4	3.9
Calvin	4.0	57.5	0.0	4.0
Bondfield	3.9	57.7	1.2	3.9
Caldwell	3.3	57.7	1.5	3.3
Mowat	3.1	57.9	1.3	3.1
Mean	3.7	54.9	1.1	3.7

TABLE IV

Analyses of Leaves of White Pine after Sulfur Dioxide Exposure Which Caused No Significant Injury

Current (1954) Needle Growth

Description of Sample	Green Pigment mg./gm., dry basis	Moisture Content, %	Conversion to Pheophytin, %	Chlorophyll ($a + b$), mg./gm., dry basis
Inner and Intermediate Fume Zone				
1. Healthy	3.6	54.1	2.5	3.5
2. Somewhat dry	4.7	48.5	4.3	4.5
3. Light green	3.6	46.3	3.2	3.5
4. Healthy	2.9	56.0	1.8	2.8
5. Healthy	3.4	55.5	0.0	3.4
6. Healthy	3.0	55.5	0.2	3.0
7. Mainly healthy, very slightly yellowing	3.1	57.3	2.1	3.0
8. Healthy	3.8	56.5	1.7	3.7
9. Mainly healthy, very slight browning at tips	3.1	54.0	1.2	3.1
Mean	3.5	53.7	1.9	3.4
Outer Fume Zone				
10. Slight browning at tips	3.1	51.4	2.8	3.0
11. Healthy	3.8	60.0	4.9	3.6
12. Healthy	3.0	59.1	4.2	2.9
13. Healthy	3.0	53.6	3.5	2.9
14. Healthy	3.1	56.6	2.3	3.0
Mean	3.2	56.1	3.5	3.1
Overall Mean	3.4	54.6	2.5	3.3

TABLE III

Effect of Sulfur Dioxide Injury to White Pine Leaves in the Inner and Intermediate Fume Zones of a Smelter Area

Current (1954) Needle Growth

Description of Sample	Green Pigment, mg./gm., dry basis	Moisture Content, %	Conversion to Pheophytin, %	Chlorophyll ($a + b$), mg./gm., dry basis
A. Acute and Chlorotic, with High Pheophytin Conversion				
1. Brown tips for 1 in. of length, dry	4.4	10.3	17.7	3.6
2. Mottled appearance, very dry	3.6	9.5	40.2	2.2
3(a). Apparently green portions	4.3	29.2	12.4	3.8
3(b). Chlorotic portions	4.2	29.2	43.0	2.4
4. Chlorotic with brown tips	4.2	16.2	49.5	2.1
5(a). Chlorotic, dry	2.8	20.4	24.8	2.1
5.(b) Chlorotic, very dry	2.8	13.1	52.4	1.5
Mean	3.8	18.3	34.3	2.5
B. Mainly Chlorotic Injury, Low Pheophytin Conversion				
6. Browning of tips	2.9	56.4	2.2	2.8
7. Chlorotic, slight yellowing and browning	2.7	55.5	3.9	2.6
8. Browning and yellowing of tips	2.6	56.0	3.6	2.5
9. Yellowing and browning over about half needle length	2.1	49.0	4.5	2.0
10. Browning of tips	2.6	55.2	3.6	2.5
11. Yellowish green, slight browning of tips	2.2	55.0	4.4	2.1
Mean	2.5	54.5	3.7	2.4
C. Mainly Acute Injury, Low Pheophytin Conversion				
12. Browning over half the needle length	3.9	53.1	1.8	3.8
13. Browning over half the needle length	3.9	48.6	2.8	3.8
14. Slightly chlorotic	3.5	49.0	4.7	3.3
15. Browning over half the needles	3.1	53.7	1.6	3.1
16. Browning at tips	3.6	54.4	2.5	3.5
17. Browning at tips	3.3	53.5	1.2	3.3
Mean	3.6	52.1	2.4	3.5

Effect of Sulfur Dioxide

Specimens of white pine leaves indicating various types of sulfur dioxide injury were obtained from the Sudbury nickel-copper smelting district in the fall of 1954. The results of the spectroscopic analyses are grouped into 3 classes (A, B, and C) in Table III. Many of these samples showed brown discolorations at the tips, or extending for about half the length of the needles. Since the brown color is the result of post-mortem oxidative changes in the tissue, there is no pigment normally present in leaves that gives this color. The brown portions were therefore removed and discarded before analysis.

It is well known that one of the acute effects of sulfur dioxide damage is to cause a rapid drying out of the affected portions of the leaves as the cells undergo plasmolysis and lose their ability to retain water. This is illustrated by the data in Section A of Table III. A concomitant action of this gas is the conversion of a considerable part of the chlorophyll in the leaf cells to pheophytin, with a corresponding reduction in overall chlorophyll content.

The data in Section B indicate a type of gas damage wherein the tissue that is chlorotic but not brown in color shows an inferior chlorophyll content but is substantially normal in regard to moisture content. The pheophytin conversion is only slightly higher than normal. Apparently, such portions of the leaves are still functioning but at a reduced rate of photosynthesis.

In Section C there is apparently little, if any, effect of the sulfur dioxide on the parts of the leaves that do not show the brown, post-mortem color. There is no doubt that such leaves can recover from the effects of gas damage and will continue to grow. Browning of the tips does not necessarily involve a lowering of the chlorophyll content of the rest of the needles. This would appear to confirm Thomas' contention[17, 19], that sulfur dioxide is not a systemic poison, but that the injury is confined to the areas that are visibly affected.

The data in Table IV indicate the analytical values for samples from trees exposed to frequent visitations of sulfur dioxide (1954 needle growth) in which the levels of concentration were insufficient to cause significant markings on the foliage. The chlorophyll content is within the normal range for white pine, the moisture content is substantially normal,

(17) Thomas, M. D., Hendricks, R. H., and Hill, G. R., *Proc. First National Air Pollution Symposium*, 142, (1949). Stanford Res. Inst.

(19) See footnote 19, page 144.

at the south end of the Detroit River, the site of a large lime and alkali industry and there is only a slight increase in pheophytin conversion. The samples have been grouped in Table IV according to location of the trees within the area affected by gas visitations from smelter operations into inner and intermediate fume zones, and the outer fume zone.

Three types of gas fumigation occur within the Sudbury area on the basis of extensive air sampling records from 7 continuous analyzers (Thomas autometers), and portable equipment transported by automobile and aircraft[7]: (1) heavy fumigations with average concentrations of about 0.75 to 1.5 ppm. or more, (2) medium fumigations of average concentrations in the range of about 0.30 to 0.75 ppm., and (3) light fumigations in the range below about 0.30 ppm. In the inner fume zone, all types of sulfur dioxide visitation may occur. The intermediate zone is subjected to light and medium fumigations almost exclusively. In the outer fume zone, the concentrations seldom exceed about 0.25 ppm.

Frequency of gas visitations in these areas varies from month to month in each growing season, but the duration of gas during these months in the inner fume zone is about 30 to 15% of the time. This duration decreases to about 20 to 7% of the time in the intermediate zone and from 15 to 5% approximately in the outer zone. The sulfur content of vegetation varies from about 2.5 to 4 times the normal range in the inner zone to about 1.5 to 3 in the intermediate zone, and 1.25 to about 1.5 in the outer zone.

Effect of Urban Pollution

The influence of urban pollution on chlorophyll content and pheophytin conversion in conifer leaves was investigated by the analysis of current growth in the autumns of 1953 and 1954 in the Greater Windsor, Ontario area, at points along the Detroit River, and at locations 15 to 20 mi. south of this river. The Detroit River area is one of the great industrial regions of North America with a combined urban and rural population on both sides of the international boundary of about 3,000,000. A description of the varied character of industrial and public activities in this area and the nature of the atmospheric pollution problem has been presented elsewhere[8, 9]. Air contaminants consist of smoke and fly ash from a large volume of vessel traffic, products of combustion from fuels, exhaust from automobiles and trucks, and aerosols, gases and vapors from metallurgical, chemical, automotive, paint, rubber, refinery, and other industries.

With regard to effects on vegetation, acute damage has been confined to the vicinity of certain specific sources of pollution. There is no widespread damage to vegetation comparable to the large areas of injury caused by "oxidants" in the Los Angeles area. The main symptoms have been due to substances such as chlorine and hydrochloric acid, sulfur dioxide, alkaline dust, hydrocarbon vapors, and excessive deposits of carbon, soot, and other solid particles on the leaves and in the stomata.

Levels of sulfur dioxide, dustfall, and suspended particulates in the area covered by the sample collections of conifer leaves are shown in Table V. Sandwich is in the Windsor high-pollution area; Riverside is a residential area of Windsor; LaSalle is a suburb near the Detroit River, about 5 mi. downriver from Windsor; Amherstburg is a small town at the south end of the Detroit River, the site of a large lime and alkali indus-

TABLE V

Levels of Contaminants in Greater Windsor and Surrounding Areas during Growing Season

Area	Sulfur Dioxide			Dustfall Range, tons/mi.²/mo.	Suspended Particulates, μg./m.³	
	Mean Range ppm.	Maximum ppm. (½-hr mean)	Duration Frequency in % of time, range		Mean Range	Maximum
1953 Growing Season, May - September						
Sandwich	0.016 - 0.113	0.52	99 - 63	46 - 90	256 - 343	550
Riverside	—	—	—	42 - 68	162 - 276	512
LaSalle	0.005 - 0.01	0.20	50 - 4	33 - 46	237	447
McGregor(a)	0.003 - 0.01	0.095	35 - 29	24	—	—
Harrow	—	—	—	44 - 49	116 - 190	300
1954 Growing Season, May - September						
Sandwich	0.003 - 0.030	0.41	80 - 24	45 - 62	133 - 174	434
Riverside	0.001 - 0.003	0.10	25 - 15	26 - 57	107 - 162	326
LaSalle	0.001 - 0.002	0.26	30 - 6	—	—	—
Harrow	0.001	0.10	10 - 15	22 - 48	73 - 118	209

(a) The results cover only a part of the growing season.

TABLE VI

Effect of Urban Pollution on Conifer Leaves—Current (1953) Needle Growth of Scotch Pine, Greater Windsor, Ont., and Surrounding Areas

Location and Description of Sample	Green Pigment mg./gm., dry basis	Moisture Content, %	Conversion to Pheophytin, %	Chlorophyll (a+b), dry basis
Chlorophyll in Leaves is Deficient				
1. Riverside (a)	4.8	55.7	6.1	4.5
2. Riverside(a)	4.6	54.3	3.4	4.4
3. LaSalle, slightly chlorotic, very dusty	4.2	53.5	5.7	4.0
4. Amherstburg, slightly chlorotic, dusty	3.9	53.9	4.5	3.7
5. Amherstburg, very dusty	4.2	51.0	1.5	4.1
6. Harrow	4.2	57.1	5.8	4.0
7. Harrow	3.8	52.9	4.6	3.6
Mean	4.2	54.1	4.5	4.0
(a) Chlorophyll in Leaves is Deficient				
8. Sandwich, very dusty	3.3	52.7	7.6	3.0
9. Sandwich, very dusty	3.3	55.6	5.3	3.1
10. LaSalle, slightly chlorotic, very dusty	2.4	47.5	5.3	2.3
11. McGregor	3.1	54.6	6.4	2.9
12. McGregor	2.8	54.1	5.6	2.6
Mean	3.0	52.9	6.0	2.8

(a) White Pine

(7) Katz, M., Anal. Chem., 22, 1040 (1950) and unpublished data.

(8) See footnote 8, page 145.

(9) Katz, M., *Air Repair*, 4, 176 (1955).

TABLE VII.

Effect of Urban Pollution on Conifer Leaves—Current (1954) Needle Growth of Spruce, Greater Windsor, Ont., and Surrounding Areas

Location and Description of Sample	Green Pigment mg./gm., dry basis	Moisture Content, %	Conversion to Pheophytin, %	Chlorophyll (a+b) mg./gm., dry basis
Chlorophyll in Leaves is Normal				
1. Riverside, short and dusty	3.1	53.6	0.0	3.1
2. LaSalle, needles healthy, rather dusty	3.4	59.5	0.8	3.4
3. LaSalle, needles healthy	3.1	57.3	0.3	3.1
4. Harrow, needles healthy, dark green	3.4	56.6	0.3	3.4
5. Harrow, needles healthy, dark green	3.8	59.1	0.1	3.8
Mean	3.4	57.2	0.3	3.4
Chlorophyll in Leaves is Deficient				
6. Riverside, needles very dusty, tree appearance fair	2.5	52.6	0.4	2.5
7. Sandwich, needles short and dusty, tree subnormal	2.3	52.1	2.5	2.2
8. Sandwich, needles short and dusty, tree subnormal	2.7	52.0	1.6	2.7
9. Amherstburg, needles dusty, tree condition apparently normal	2.5	54.1	4.1	2.4
10. Amherstburg, needles short, tree condition apparently normal	2.5	57.6	2.3	2.4
11. Amherstburg, tree condition apparently normal	2.4	56.0	1.0	2.4
12. LaSalle, 1953 needles, slight browning at tips	3.1	52.9	8.2	2.8
13. McGregor, needles light green, tree condition apparently normal	2.1	55.3	3.5	2.0
14. McGregor, needles chlorotic, tree condition apparently normal	1.6	56.1	5.2	1.5
15. Harrow, needles browned at tips, very dusty, tree condition apparently normal	2.7	56.4	1.8	2.7
Mean	2.4	54.5	3.1	2.4

try; McGregor is a village and rural area about 15 mi. south of Windsor; and Harrow is a small town about 20 mi. south of Windsor.

The sulfur content of vegetation in this area decreases notably with distance from Windsor. Values for a number of species are about 2 to 3 times higher in Windsor than at McGregor or Amherstburg. The sulfur content at Harrow, Ont., is somewhat higher than at McGregor. This picture of sulfur accumulation in vegetation is more consistent with the known levels of sulfur dioxide contamination of the atmosphere than with any influence that might be attributed to sulfur variability in the soil.

Chlorophyll and pheophytin conversion values for Scotch pine samples are shown in Table VI, and for spruce samples in Table VII. It is apparent that the results may be grouped into 2 classes. In the first group the chlorophyll content is substantially normal, whereas in the second group the leaves are deficient in chlorophyll. It is considered that the effect of sulfur dioxide is minor compared to the influence of dust and soot accumulations on the leaves and in the stomata. Levels of sulfur dioxide in this area were in general higher and of greater frequency during the 1953 growing season than in 1954. This may be the reason for the consistently higher pheophytin values in the 1953 samples.

In contrast to sulfur dioxide markings, the effects of dust and soot accumulations on leaves are difficult to assess by visual examination of the foliage. The evidence from the chlorophyll analyses indicates that exposure to such conditions may result in lowered vitality and poor growth of the plant associated with a reduction in photosynthesis.

Discussion

Air-pollution damage to vegetation produces a variety of gross symptoms on leaves which may have similar features as to color changes, location of lesions, and boundary characteristics. It may not be possible to distinguish between sulfur dioxide markings and fluorine symptoms on the basis of purely visible examination. Even the so-called "silver leaf" damage caused by the atmospheric interaction products of gasoline vapors and ozone or oxides of nitrogen, so often encountered in the Los Angeles area, may be matched under certain conditions by sulfur dioxide. The order of susceptibility of various species to air pollution damage is a useful guide as to the probable causal agent. Chemical analysis of the leaf tissue provides additional help in diagnosis. However, air-pollution damage may be non-specific in character, especially when it is due to the deposition of carbon, soot and dust from smoke, haze and other aerosol contaminants of wide variety in the urban atmosphere. In this case, if there is sufficient deposition on the leaves, and inside the guard cells and stomata, the resultant clogging of the entry passages would hinder gaseous exchange or photosynthesis and respiration.

The evidence in the present study on chlorophyll and pheophytin conversion in conifer leaves indicates that acid gases, such as sulfur dioxide in sufficiently high concentration, convert the chlorophyll pigments into the corresponding pheophytins. This process does not take place to an appreciable extent, however, unless the threshold value for sulfite in the living cells is exceeded. The effect may be produced by either relatively short exposures to high concentrations of gas or more prolonged exposures to lower concentrations. Transformation of an appreciable proportion of chlorophyll to pheophytin is accompanied by visible symptoms in the tissue, such as plasmolysis, shrinkage of cells, and fading of the normal green color. When these symptoms have progressed to the post-mortem stage, there is of course no chlorophyll or pheophytin left in the injured portions of affected leaf tissue. The color may then turn red or reddish-brown if anthocyanin pigments, associated with the appearance of large amounts of sugar in the cells, are formed. Eventually such leaves turn brown because of post-mortem oxidative changes. These color changes are characteristic of conifers. In other species, the destruction of the chlorophyll, pheophytin, and other pigments in the chloroplasts results merely in the appearance of

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Tailoring the Air-Pollution Ordinance to Community Needs*

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In a recent study[1], it was concluded that approximately 10,000 United States communities have local air-pollution problems. By breaking down this estimate with respect to population and urbanization (Table 1) and by subtracting from this breakdown a similar one for the number of these communities which already have some form of specific air-pollution-control legislation (Table II), it is possible to estimate the number of jurisdictions in which there is need for some form of legislation (Table III). It will be seen that over 95% of this need lies in communities of less than 25,000 population. The percentage would be even higher if it were extended to include those additional localities which, because they have no present local problem, are also without any form of air-pollution-control ordinance. This is so because these are the communities with most to gain by the adoption of preventive-type legislation, such as properly conceived zoning ordinances. Because of the magnitude of the legislative need in communities of under 25,000, and the fact that this aspect of the problem has seldom been discussed heretofore, the remainder of this paper will be devoted to this specific aspect of the problem.

(1) Stern, Arthur C., "Air Pollution Control: Administrative Needs and Patterns," First International Congress on Air Pollution, Am. Soc. Mech. Engrs., New York City, March 1, 1955.

*Presented at the Dust and Fume Product Group Session, Foundry Equipment Manufacturers Association, at Washington, D. C., April 15, 1955.

Model Ordinances

It is not intended here to present standard or model ordinances or to suggest desirable words, phrases, paragraphs or provisions to incorporate in local ordinances. Perhaps the Public Health Services should at a later date fill this need by publishing an annotated catalog of such of these phrases as have been found useful in ordinance construction under a wide variety of conditions. For the present, all that can be offered along these lines is a note of caution against the use of stock ordinance provisions as stereotypes.

It is always wise first to inquire into the local situation that gave rise to each such provision, and be assured that it is parallel to one in the community considering its adoption. As a general caution, it should be recognized that most ordinance provisions in common circulation in the United States today stem from the needs of a handful of large cities whose predominant problem was black smoke from the combustion of high-volatile bituminous coal. Where the community is either small or where the major problem is other than soft-coal smoke, the fit between the model ordinance and the community is likely to be poor unless a careful job of tailoring is undertaken to match the ordinance to the community. The tailoring process consists essentially of seeking the answer to 4 questions, as follows:

1. *What Is the Nature of the Air-Pollution Problem of the Community?*

The answer is best exemplified by the oft-told tale (which may be fact or fiction) of the inland community, far from navigable water, which adopted provisions specifically limiting the emission of smoke from steamships, because it happened to be part of the model ordinance sent to the town in response to their request for help. Whether true or not, this tale serves to highlight the need for first carefully delineating the elements of the local problem and then seeking to match each element with an appropriate word, phrase or provision.

2. *What Local Official or Body is Available to Administer an Ordinance?*

This would offer no problem if one or more new administrative positions or boards could be created, as is the practice in large cities. However, in the small jurisdictions whose problems are being considered, financial considerations almost invariably prevent the implementation of an air-pollution control ordinance with full-time personnel or equipment. Therefore, the choice must almost always be either to add air-pollution control to the duties of a municipal employee or to face up to the fact that the community is too small to afford even a part-time air-pollution-control official.

In the former case, the procedure is to scrutinize the roster of present job titles and duties to seek the job description most closely akin to air-pollution-control officer, and then to find out if the incumbent in that job has enough spare time to take on this additional assignment. In communities where this procedure was followed, it has resulted in the job of air-pollution-control officer being bestowed variously on the village engineer, the plumbing inspector, the

TABLE I
Estimated Number of United States Communities Which Have a Local Air-Pollution Problem

Population in Thousands	Number of Communities		
	Urban	Rural and Suburban	Total
Over 25	600	200	800
10 - 25	700	200	900
5 - 10	500	300	800
3 - 5	1100	500	1600
1 - 3	1200	2000	3200
0 - 1	1200	1000	2200
Total	5300	4200	9500

TABLE II.

Estimated Number of United States Communities Having Specific Legislation Concerning Air Pollution

Population in Thousands	Number of Communities		
	Urban	Rural and Suburban	Total
Over 25	400	40	440
10 - 25	380	60	440
5 - 10	360	60	420
3 - 5	260	40	300
1 - 3	200	100	300
0 - 1	130	20	150
Total	1730	320	2050

building inspector and the town sanitarian. In some jurisdictions, the first thought is to add air-pollution-control to the many other responsibilities of the police. Wherever this has been attempted, it has been unsuccessful, and should be avoided. The only function the police should have in enforcement is the actual carrying out of orders of the court or of the city, town or village board with respect to the collection of fines, the arrest of convicted persons, or the sealing of equipment or premises.

When the community is too small to undertake the administration of a control ordinance, it is desirable to have the county or state take over the responsibility. In fact, if there is a strong county or state control program based upon state-wide legislation, even the community which can afford part-time administration might prefer to let the state do the job for it. Properly drafted state legislation applies to all its subdivisions, but does not prevent any subdivision from enforcing more restrictive local legislation. When such state-wide legislation exists, a local jurisdiction achieves no benefit from adopting provisions less restrictive than the state's if it is able to enforce the ordinance with its own personnel, nor from adopting provisions more restrictive than those of the state if it is unable to enforce its own provisions.

3. *Is the Administrative Official or Body Capable of Enforcing the Ordinance?*

It does not make sense to incorporate in a local ordinance requirements for stack sampling or chemical analysis beyond the ability of the administrator or his staff to perform, to have it done by someone else in the local administration, or to pay for having done by outside consultants. Similarly, plan filing and approval schemes will work only if the administrator has the competence and time to effect their review. This is rarely the case in smaller communities. Registration of new installations and re-registration of old ones is a purely clerical operation and can be handled in even the smallest of jurisdictions. But the effectiveness of a registration procedure will be nil unless it is backed up by the readiness of the administration to do or pay for stack sampling and chemical analysis.

To meet these various needs, several recent ordinances for small communities have specifically given the administrator authority to hire outside consultants to perform the necessary tests and, under various restrictions, to expend public funds for this purpose.

4. *How Good a Job of Enforcement is Desired or Expected?*

The bill drafters should give to the administrator the type of punitive tools the community wishes to have used. If they want tough enforcement, all tools, such as the right to seal equipment, should be provided.

Because of these considerations, the smaller the community, the simpler the ordinance, so that in the small ones (with no enforcement personnel, either full or part time, and no capability of technical enforcement) it becomes a simple paragraph stating prohibited emissions. It is important, however, that even the very smallest jurisdiction include among its ordinances a paragraph of this sort to set forth the community's intent to declare certain specified emissions to be nuisances, per se, requiring correction. Without such declaration of legislative intent, much time, money, and effort may be required to prove that an objectionable air-pollution source is, in fact, a nuisance.

Zoning Ordinances

A zoning ordinance supplements an air-pollution-control ordinance in accomplishing the purposes sought by both. Such zoning takes several forms. One is the creation of only residential and commercial zones and the wilful omission of industrial zones. No surer way of stifling the growth of a community has yet been invented. This type of zoning was devised to protect the character of commuter suburbs. Several have lived to regret their lack of self-sufficiency when the pattern of commutation shifted. The solution is not to "zone out" all industry, but rather to "zone in" industry which will be good neighbors.

Another unwise zoning concept is that of the unconditional exclusion from the

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TABLE III

Estimated Number of United States Communities Which Have a Local Air-Pollution Problem But Which Do Not Have Specific Legislation Concerning Air-Pollution

Population in Thousands	Number of Communities		
	Urban	Rural and Suburban	Total
Over 25	200	160	360
10 - 25	320	140	460
5 - 10	140	240	380
3 - 5	840	460	1300
1 - 3	1000	1900	2900
0 - 1	1070	980	2050
Total	3570	3880	7450

On the Transport of Atomic Debris in the Atmosphere*

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The fate of radioactive debris which is injected into the atmosphere by an atomic explosion is of great interest in a meteorological sense. First, there is the problem of estimating what will happen to the debris and second, what new knowledge concerning atmospheric processes can be gained through the study of the unique tracer. As of June 4, 1953, there had been 31 nuclear devices detonated by the Atomic Energy Commission at its Nevada Proving Ground, located about 70 mi. north-northwest of Las Vegas. The Weather Bureau has cooperated with the Atomic Energy Commission in a large-scale program to collect daily samples of radioactive debris near the ground during atomic-test periods, and to study the meteorological aspects of the problem.

The tremendous heat source resulting from the detonation of a nuclear weapon in the atmosphere produces a bouyant bubble of intensely hot gases which serves not only to carry aloft the debris resulting from the fissions and subsequent disintegration of the bomb casing and auxiliary equipment, but also to suck up great amounts of soil and dust, much of which is rendered radioactive. As the buoyant bubble rises, it cools both by radiation and by entrainment of the surrounding air. The ascending column of air and debris continues to rise until it has cooled to equilibrium with its environment, usually within about 15 min. The height to which the debris rises is governed by the character and intensity of the burst and by the stability of the atmosphere.

Typically, just after the ascending motion has ceased, the cloud of radioactive debris consists of a long, slender "stem," capped by a broader "mushroom" top, which in most cases reaches to the base of the stratosphere. Although considerable debris is contained in the stem, the great bulk of the material is in the mushroom cap. The subsequent history of the debris depends on many factors, including the size distribution and fall velocity of the particles, the nature of the wind field, the eddy diffusivity, and the scavenging of particles by precipitation.

At any given level, the trajectory of the *primary cloud*, i.e., that portion of the initial cloud which moves with the winds and is unaffected by diffusion or fallout, can be computed by conventional meteorological techniques. The determination of the movement of all the debris is a very much more complex problem. In this report, we will be concerned only with the relatively long-range aspects of the problem, the movement of debris at distances greater than 200 mi. from the test site.

Sampling Techniques

For Operations TUMBLER and SNAPPER, in the spring of 1952, the Weather Bureau, in cooperation with the New York Operations Office of the Atomic Energy Commission[1], conducted a large-scale program to collect daily samples of radioactive debris at 120 Weather Bureau stations throughout the United States (Fig. 1). Two types of samples were taken, one to measure the debris deposited on a horizontal surface, the other the debris in the air near the ground. The deposited debris was collected by exposing 1 ft.^{2} sheets of gummed paper on a horizontal stand about 30 in. above the ground at 91 stations scattered throughout the country. Three such papers were exposed simultaneously for a 24-hr. period at each station. Airborne debris was collected at 51 stations within 1000 mi. of the proving ground by a modified tank-type vacuum cleaner which sucked air through a 4-in.-diameter dust filter at the rate of about 35 ft.^{3}/min. Filters were changed every 24 hr.

The samples were mailed daily to the New York Operations Office, where they were reduced to ash, sealed in a plastic tape and fed through counters which automatically counted and recorded the beta activity in each sample. Activity measured on the gummed papers is reported in terms of the number of disintegrations per minute per square foot of paper collected over one day (d/m/ft^2/day). Air filter measurements are in terms of disintegrations per minute per cubic meter of air (d/m/meter^3).

All significant activity measurements were extrapolated to the sampling date by ascribing the measured activity to a particular burst and assuming that the decay has been proportional to $t^{-1.2}$

* Reprinted from Bulletin of The American Meteorological Society, **35**, 315-25 (Sept. 1954) by permission of the American Meteorological Society.

(1) Eisenbud, M., and Harley, J. H., *Science*, **117**, 141-147 (Feb. 13, 1953).

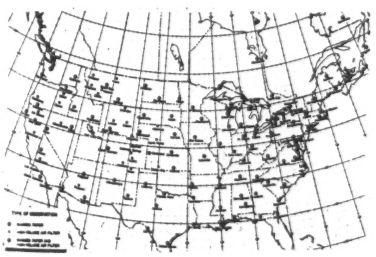

Fig. 1. Location of Sampling Stations

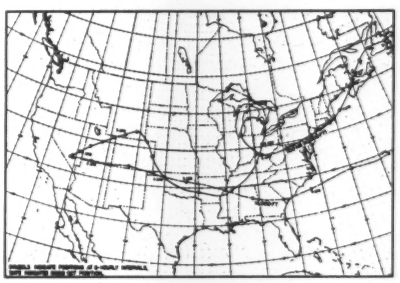

Fig. 2. Meteorological Trajectories of the Debris from the First Burst, April 1, 1952

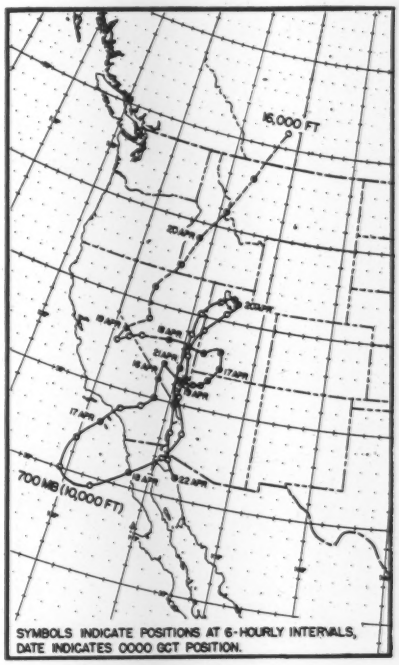

Fig. 3. Meteorological Trajectories of the Debris from the Second Burst, April 15, 1952

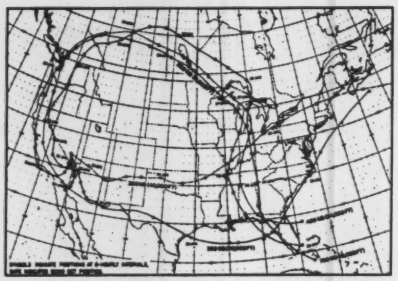

Fig. 4. Meteorological Trajectories of the Debris from the Third Burst, April 22, 1952

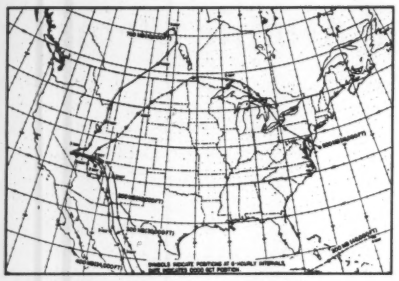

Fig. 5. Meteorological Trajectories of the Debris from the Fourth Burst, May 1, 1952

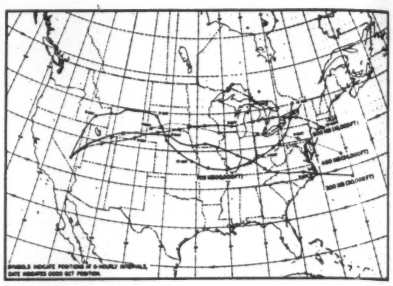

Fig. 6. Meteorological Trajectories of the Debris from the Fifth Burst, May 7, 1952

where t is the time since the burst [2]. However, there is considerable uncertainty in determining which burst is responsible for the activity at a given station, although the bursts were separated by several days. In addition to considering the computed meteorologieal trajectories of the primary cloud and estimating the low-level trajectories from the surface and gradient winds, it is also necessary to note the arrival of increased activity at the various stations. Even with these considerations, it is not always possible to determine when activity from a new burst arrives at a station. The onset of precipitation frequently results in increased activity on the gummed paper which may erroneously be ascribed to the arrival of debris from a more recent burst. Changing wind speeds or directions may also cause increases in activity not associated with a new burst; this is especially true in the dry, dusty areas of the Southwest. Since the samples are not measured until several days, and in some cases weeks, after the date of collection, the extrapolation factors can be quite large, as much as 2 orders of magnitude if the collection was made on the day of the burst. Other sources of difficulty are that minor contamination of the sample in handling or counting can result in very high extrapolated values, also mixed debris from 2 or more bursts would, in general, all be ascribed to the latest one. These factors, coupled with the tendency to ascribe debris to the latest burst when there is some doubt as to its origin, make for a bias toward reporting higher activity than actually existed.

(2) Way, K., and Wigner, E. P., *Phys. Rev.*, 73, 1318 (1948).

Comparison of Air Filter and Gummed Paper Observations

It is evident that the gummed papers serve to measure a somewhat different phenomenon than the air filters. The former collects material which settles out on a horizontal surface, while the latter measures the concentration of activity on particles suspended in the atmosphere near the ground. The difference between the 2 types of measurement is most evident when the effects of precipitation are examined. In general, there is no observable difference in the radioactivity collected by the air filters on days with no precipitation as compared with rainy days. The failure to detect the effects of precipitation on the air filters may be, in part, due to the poor resolution inherent in a 24-hr. observation that would mask any short-term effects.

The amount of activity collected by the gummed papers, however, is highly correlated with the occurence of precipitation. On the average, when debris is aloft, about 10 times more activity will be found on the gummed papers during days with precipitation as compared with dry days. This effect on the gummed-paper observation must be indicative of an even larger difference in what occurs on the ground, since so much of the precipitation spatters or runs off the gummed-paper stands. The increased activity in rain on the gummed paper, with no corresponding effect on the air filter, indicates the bulk of the activity is carried down in the precipitation elements, rather than in the air moving with the falling droplets. At present, there is no evidence that the radioactive particles serve as condensation nuclei, as most are non-hygroscopic, spherical particles. This would indicate that the falling precipitation elements are effective scavengers of small particles. However, studies of the collection efficiency of falling raindrops[3] indicate a relatively low efficiency in collecting particles smaller than 5 μ, although the mass median diameter

(3) Langmuir, L., *Meteor.*, 5, 175-192, (Oct. 1948).

TABLE I
Spring, 1952, Atomic Tests

Burst	Date	Time (GCT)	Type	Height of top of cloud (MSL)
1	Apr. 1	1700	Air drop	16,000 ft.
2	Apr. 15	1730	Air drop	16,000
3	Apr. 22	1730	Air drop	42,000
4	May 1	1630	Air drop	44,000
5	May 7	1215	300-ft. Tower	34,000
6	May 25	1200	300-ft. Tower	41,000
7	June 1	1155	300-ft. Tower	37,000
8	June 5	1155	300-ft. Tower	42.000

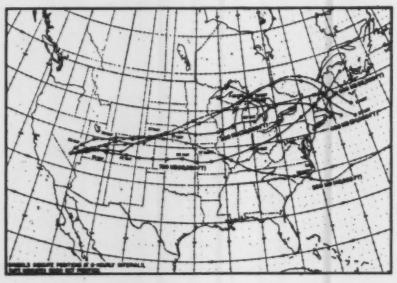

Fig. 7. Meteorological Trajectories of the Debris from the Sixth Burst, May 25, 1952

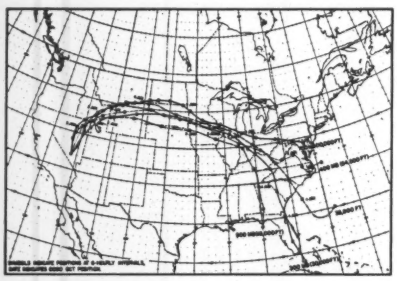

Fig. 8. Meteorological Trajectories of the Debris from the Seventh Burst, June 1, 1952

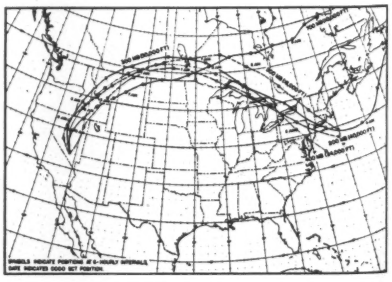

Fig. 9. Meteorological Trajectories of the Debris from the Eighth Burst, June 5, 1952

of radioactive particles seems to be strongly peaked in this region. Since there is no information available concerning the initial concentration of radioactivity in the cloud, or of the concentrations aloft at any given time, it is difficult to estimate how efficiently the falling raindrops scavenge the air. The greater density of radioactive particles and electrostatic effects may be important. Experiments are being conducted to determine the changes in concentration with time in both the air and the precipitation during the course of a rainstorm.

Spring, 1952, Atomic Tests

The Nevada atomic tests of the Spring of 1952 consisted of the 8 bursts listed in Table I.

Since the heights of the cloud tops were estimated from aircraft or ground observations, it must be assumed that some uncertainty exists as to the exact heights, particularly for the higher clouds.

Levels of Activity

Since the activity contained in the samples is not measured until several days after collection, the natural radioactivity from radon and thoron daughters is negligible. Most gummed papers exposed prior to the first test had less than 5 d/m/ft.^{2}/day when counted; the highest average value at any station was about 10 d/m/ft^2/day. For the air filters, background activity ranged from 0 to 0.05 d/m/meter^3.

Excluding the area within 200 mi. of the test site, the highest activity observed on the gummed papers was 8×10^6 d/m/ft^2/day, at a station about 330 mi. from the test site. At distances over 2000 mi. from the site, the maximum observed activity was 1.7×10^5 d/m/ft^2/day; both values occurred on days with rain. The highest air filter measurement occurred at a station only 250 mi. from the test site, where 1.3×10^5 d/m/meter^3 was observed; however, this was apparently an exceptional case, since the highest value excluding this station was 6.8×10^3 d/m/meter^3.

Meteorological Trajectories

For each of the bursts, meteorological trajectories of the primary cloud were computed for all standard pressure surfaces from the 700-mb level to the top of the cloud. In a few cases, where the level of the top of the cloud departed significantly from a standard pressure surface, trajectories were computed at additional levels. All trajectories were constructed by assuming that the flow pattern on each 6-hourly upper-air chart remained constant for a period from 3 hr. before until 3 hr. after map time. The trajectories of debris from the 8 bursts of this series are shown in Fig. 2-9.

For a period of several days following each test, predictions of the areas in the United States expected to have experienced fallout were made daily for the New York Operations Office of the Atomic Energy Commission. These predictions were based on the trajectories shown (except for burst 2, which will be discussed below) plus a consideration of the low-level flow patterns.

Examples

Fig. 10a-d show the results following the first burst. Isolines of radioactivity found on the gummed papers (d/m/ft^2) are shown by solid lines, the areas of fallout are shown by dotted lines, shad-

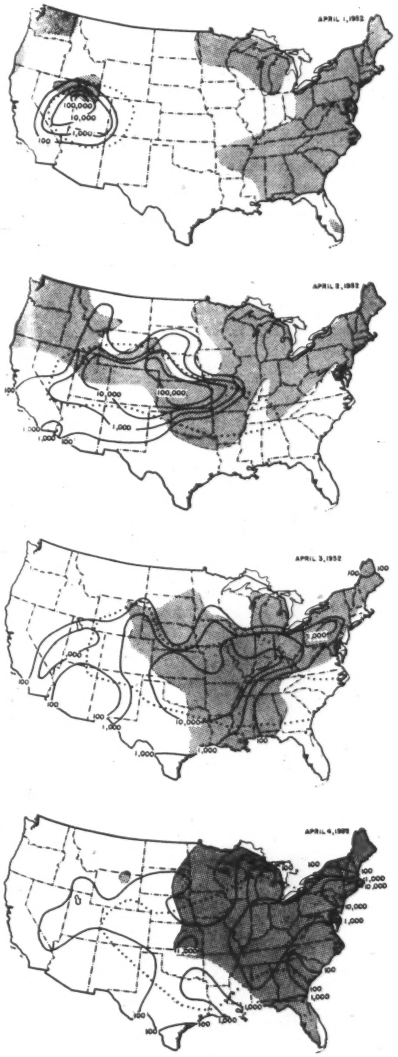

Fig. 10a-d. Predicted (Dotted Lines) and Observed (Solid Lines, d/m/ft^2/day) Areas of Ground Deposition of Radioactive Debris Following the First Burst, Precipitation Areas Indicated by Shading. Maps are for the 24-hr. Period Beginning 1230 GCT on the Dates Shown.

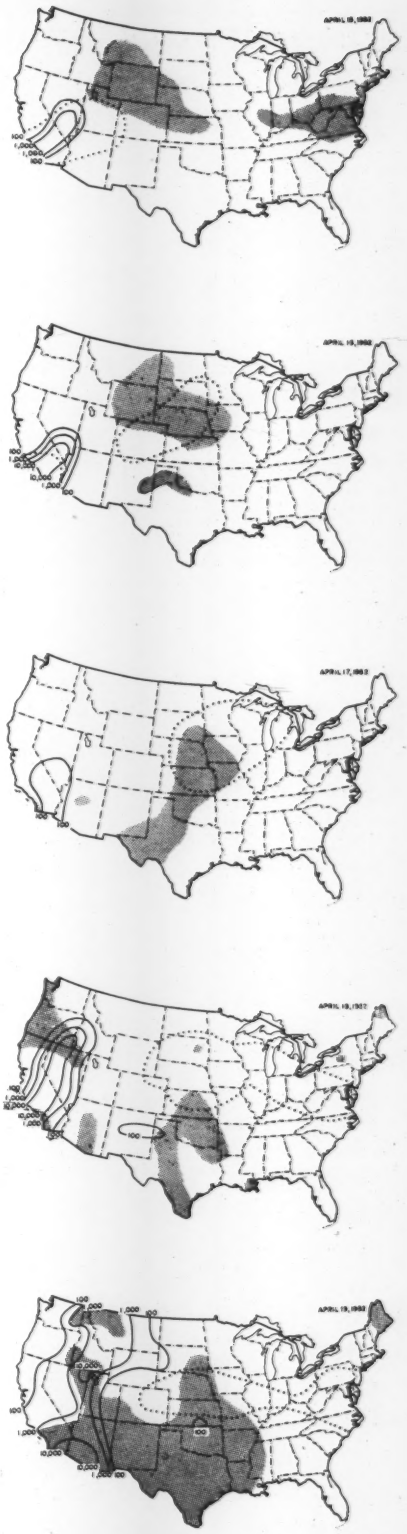

Fig. 11a-e. Predicted and Observed Areas of Ground Deposition Following the Second Burst.

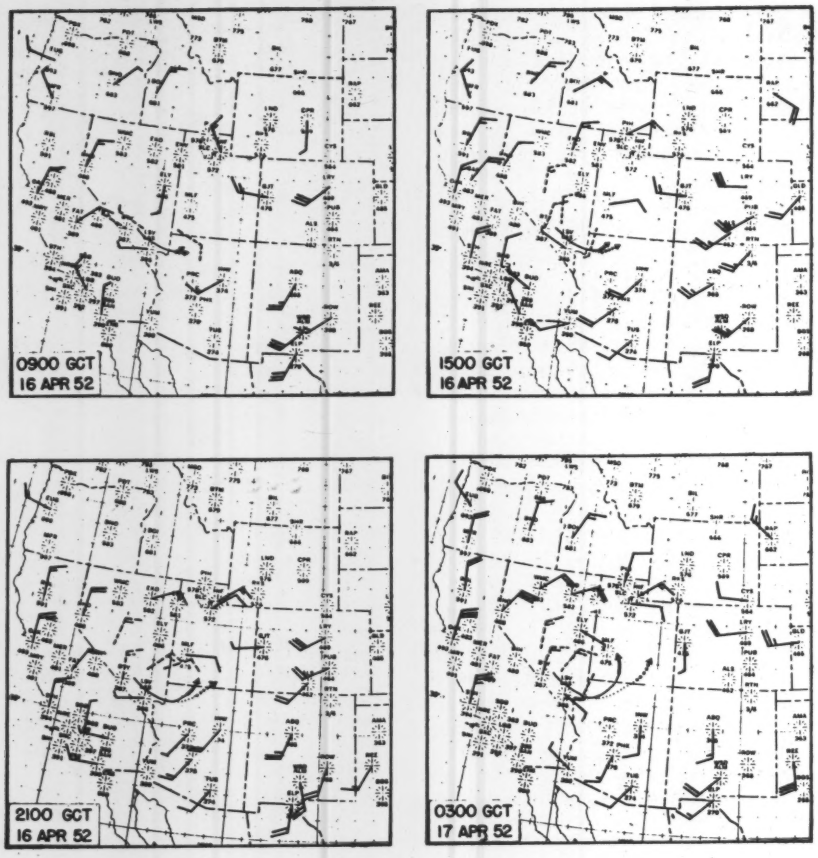

Fig. 12. Winds at 16,000 ft. Following the Second Burst (see text)

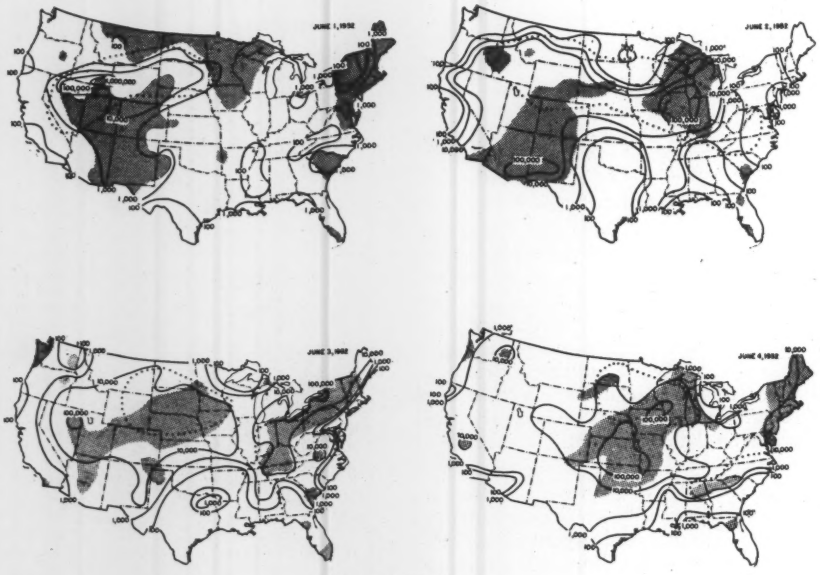

Fig. 13 a-d.

ing indicates precipitation areas. As can be seen, reasonably good agreement exists between observed and predicted areas of fallout.

Fig. 11a-e show the results following the second burst. Here, it is obvious that our attempt to predict areas of fallout for more than 24 hr. following the burst was a failure. The original computation of the 16,000-ft. trajectory showed an eastward movement of the cloud; instead, debris was found in the far western states beginning on April 18. Fig. 12 shows the 16,000-ft. winds for 4 successive 6-hr. maps beginning 0900 GCT, April 16. The solid wind-arrows represent stations in the routine meteorological network, the dashed wind-arrows indicate observations from the special station established by the Air Weather Service in connection with the atomic tests. These latter were not available at the time the original trajectories were computed. The trajectory originally computed for the 16,000-ft. level is shown by a dotted line; the revised trajectories, based on the additional wind information *and* a knowledge of where radioactivity actually was found, is indicated by the solid line. The portions of the trajectories from 3 hr. before to 3 hr. after map time are indicated by heavier lines. It is apparent that the failure to realize the significance of the light southerly wind at Ely on the 0900 GCT chart of April 16 led to the assumption of a shear line rather than a closed cyclonic circulation over southern Nevada; also the easterly wind at MLF at 161500Z might have suggested the existence of the closed circulation, were it not so weak. Although the complex path followed by the trajectories from this burst is indicative of a light, poorly defined wind field and not too much credence can be placed on the exact positions shown, the agreement with the observed deposition of debris is quite good. It is interesting to note that the 16,000-ft. trajectory stayed within a few hundred mi. of the test site and did not pass near any stations of the monitoring network until April 18.

The results of fallout monitoring for several days following the seventh burst are shown in Fig. 13a-13d. This was a tower burst and debris from this burst was responsible for the highest activity observed during this series of tests at most of the stations in the eastern and central states. The lack of vertical wind shear along the trajectories coupled with precipitation over the western Great Lakes region during the period beginning 1830 GCT, June 2 resulted in relatively high levels of activity in this area. A similar situation prevailed in the north-

(continued on page 183)

Fume Problems in Electric Smelting and Contributions to Their Solution*

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Elektrokemisk A/S
Oslo, Norway

Smelting Mechanism and Fume Generation

In electric smelting furnaces of the type used in the production of carbide and ferro-alloys, a mixed charge of lumpy oxide and coke breeze descends slowly along vertical electrodes. The charge is heated to reaction temperatures of about 2000° C. or more by electrical resistance in the charge and by submerged arcs playing between electrode and charge. At least for slag forming reactions, presumably, a bed of coke is floating in the slag, and a large number of small arcs are playing between the tips of the electrodes and the coke. The oxide charge is simultaneously reduced and fused by contact with the superheated coke bed. In this way steep temperature gradients are established and gradual softening of the charge is avoided as much as possible by proper selection of the raw materials.

The smelting zone is covered with a 1 ft. to 4 ft. layer of cold charge which acts as a dust filter and a medium for heat interchange for the reaction gases.

This smelting mechanism gives for many electrothermal processes a very high thermal efficiency, but there is always a tendency towards formation of fumes due to the local, very high temperatures in the arc zones.

Many of the common metals and oxides have considerable vapor pressure in the temperature region 2000-2500°C., which can explain the fume formation. Most likely, a high proportion of the fumes is formed by distillation of metals like Ca, Mg, Mn, Fe, Si, and Al in the arc zones.

The furnace gas which ascends through the charge, mainly CO, will carry the fumes through the charge bed to the surface of the charge. Here the gas is burned with oxygen from the air in all open top smelting furnaces, and very small particles of oxide fumes are formed.

Fig. 1 shows an electron microscope photograph of fumes from a ferrosilicon furnace. A high proportion of the fume is spherical particles of silica of 0.01 to 0.1 micron. The peculiar shape of the particles indicates that the fume has been formed by solidification from liquid phase, probably from condensed SiO vapor in the gas. In open furnaces the burned reaction gas is immediately diluted with enormous quantities of air, and precipitation of the fumes presents serious technical and economic problems due to very small particle size, surface characteristics of the fumes, low concentration, and large gas volume.

In closed electric furnaces unburned CO gas is collected below the furnace roof. Presumably the distilled metals react with CO during cooling of the gas, and the metals are reoxidized to the lower oxides FeO, MnO and SiO, accompanied by formation of carbon as soot.

Examination of fumes precipitated from unburned furnace gas shows a very complex chemical and physical composition. As seen from the electron microscope photograph in Fig. 2, the particles are very much larger and of a ragged shape. This explains the experience from the use of closed furnaces that unburned CO gas is easily cleaned by simple, conventional methods, like wet mechanical scrubbing.

Gas Volume and Fume Concentration

The volumes of CO gas from electric smelting furnaces are small, compared to the gas volumes from other metallurgical operations. However, the furnace gas in the open top furnaces is diluted with large quantities of air, which make gas cleaning expensive.

For FeSi smelting, the fume concentration varies considerably with the quality of the raw materials, efficiency and skill of the operating personnel.

From Elektrokemisk A/S, Fiskaa Verk, Kristiansand, South Norway, the following data have been reported in the production of 75% FeSi. See Table I.

The fume concentration in the unburned CO gas is always rather high, in the order of 75-300 grams per Nm^3, and the gas volume is 1300-1500 Nm^3 per metric ton of FeSi.

For open-top furnaces of 6000-8000 kw load, the gas volume drawn off through the stack is about 200.000 Nm^3 per metric ton of FeSi. This means that the concentration of true reaction gas in the stack gas is only 0.5-1.0%, while the concentration of fumes is 0.5-2 grams per Nm^3. It is easy to understand that any collection and cleaning of this gas must require an extensive installation.

Open and Closed Furnaces

The majority of the smelting furnaces for carbide and ferro-alloys is still of the open type. However, due to the potential value of the CO gas and the heavy pressure brought by the authorities on the plants to overcome air pollution, a gradual change over to closed furnaces is underway.

Closed electric furnaces are being used successfully for processes and raw materials which give smooth operation

*Presented at the 48th Annual Meeting of the Air Pollution Control Association at Detroit, Michigan, May 23-26, 1955.

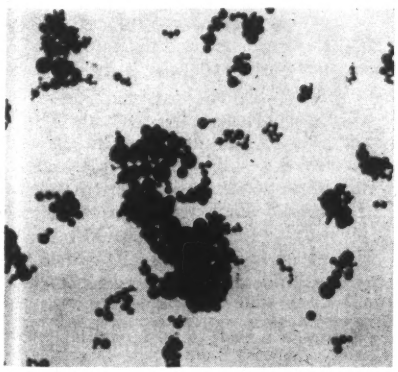

Fig. 1. Silica Dust from Open FeSi Furnace at Fiskaa Verk. Magnification 34.500x

Fig. 2. Silica Dust from Unburned CO Gas Collected at Fiskaa Verk. Magnification 28.600x

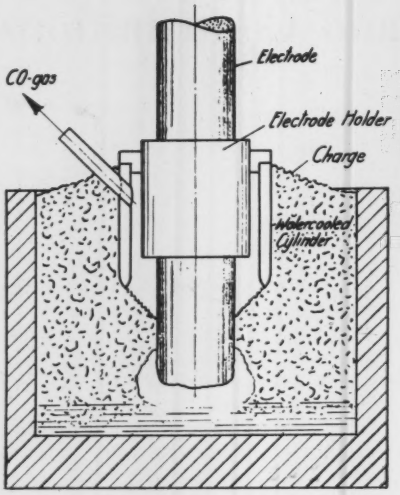

Fig. 3. Gas Collection in "Open" Furnace

without formation of bridges and hangings, and where regular poking is unnecessary.

The so-called rotating hearth furnace (type Ellefsen) [1] has proved to facilitate operation of closed furnaces for carbide and ferro-alloys. The rotating feature has also been adopted in the U. S. phosphorus industry [2]. When 3 electrodes are arranged in the equilateral triangle, the contents of the furnace hearth are being renewed during the 120° rotation of the furnace. Thereby, the formation of crater-walls in the furnace is avoided.

For most types of closed furnaces, screening of the raw materials and removal of most of the fines below 3-5 mm is a necessity. Disposal of the fines creates problems. Many large carbide plants in Europe and U. S. A. are today operating partly closed and partly open furnaces. Screened lime is used for the closed furnaces, while the fines, together with lumpy lime, are smelted in the open furnaces with more or less success.

Smelting men all over the world are looking for a cheap process for agglomeration or briquetting of fines.

Special problems are encountered in the production of high silicon ferro-

(1) Ellefsen, Tonnes, "The 'Elkem' Rotating Arc Furnace for Electrothermic Process," *J. Electrochem. Soc.*, 89, 307 (1946).

(2) Striplin, M. M. Jr., McKnight, David, Megar, G. H., and Potts, J. M., "This Phosphorous Furnace Rotates," *Chem. Eng.*, 58, 108-111 (1951).

Fig. 4. Experiments with Collection of Unburned Gas in Open FeSi Furnace at Fiskaa Verk. In Foreground Pneumatic Stoking Machine.

alloys like 75% FeSi, which is today the main product in the Norwegian smelting industry. Quartz, which is the main constituent of the charge, has a melting point of about 1700° C. Unfortunately, quartz has a tendency to soften and form a sticky paste in the furnace. This causes bridges and crust formation and sometimes narrow craters in this production. Presently all high-grade silicon alloys are produced in open furnaces, due to the high temperature of the furnace top as well as the necessity for frequent poking in the charge.

Elektrokemisk has lately made an attempt to collect unburned CO gas in an FeSi furnace at Fiskaa Verk, under such conditions that it is possible to poke in the furnace during regular operation. For this purpose the gas is collected around the electrode whereas the main part of the surface of the furnace remain open [3].

The experimental furnace is equipped with a 43-in. dia. Soderberg electrode with about 2200-2300 kw load. During the test period the furnace was operated continuously in the production of 45-50% FeSi with normal power and raw material consumption.

The gas recovery was excellent. Except for a few blue flames on the surface of the charge, the gas was drawn off through a water-cooled pipe leading to a simple, wet scrubber. Fig. 3 shows the principles of this simple gas collecting system, while Fig. 4 shows a photograph of the furnace in operation.

One of the striking advantages of this collection system is that the surface of the charge is cold so that the operator very conveniently can use his crust-breaking machine or poking equipment if required.

(3) Norwegian Patent No. 72,082.

TABLE I

Production of 75% FeSi

Operating Conditions	kwh per ton	kg quartz per ton	Nm^3 CO per ton	g SiO_2 per Nm^3 gas
Good	9 000	1 700	1 268	75
Fair	9 600	1 825	1 360	164
Unsatisfactory	10 450	2 060	1 540	296

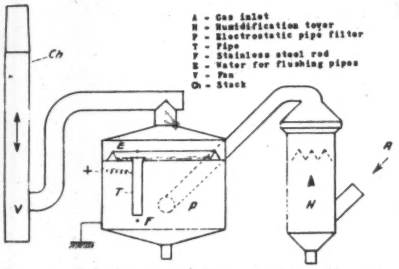

Fig. 5. Schematic Outline of Gas Cleaning Plant

As a result of the first two months' operation it seems that gas collection in this way can easily be carried out in the production of 45-50% FeSi.

Operation of 75% FeSi will soon be tried. A detailed publication of the tests is in preparation.

Actually, the collection of gas in closed furnaces is based on the same principles and designs. Therefore little trouble is expected using this simplified gas collection for 3-phase carbide and ferro-alloy furnaces. We believe that this new design will suit particularly well existing furnaces of small or medium sizes.

Gas Cleaning

Cleaning of gas from open top electric smelting furnaces is always expensive, and often technical problems are involved due to the very low particle size and dust concentration, as well as to the large volumes of gas that must be handled. Only a few gas cleaning plants have so far been installed for gas from open furnaces [4]. One highly sucessful installation is operated in France by the well known Pechiney company at Riouperoux. The installation consists of two 6,000 kw rotating hearth furnaces for silicon metal. The first furnace was built in 1950. Each furnace has been provided with a separate gas cleaning plant designed and delivered by La Societe de Purification Industrielle des Gaz (S. P. I. G.) in Paris.

Seventy-two thousand m^3 per hour (50°C) of gas is treated in each plant. A schematic outline of the same will be seen from Fig. 5.

The scrubbing and humidification tower (H) is cylindrical, 4.2m. in diameter and 8 m. high, or 250 $m.^3$ volume, which corresponds to a retention time of 12.5 seconds. Each tower has 64 water spray nozzles for 80 lbs. pressure.

The electrostatic filters (P) are of the pipe type and are built in two compart-

(continued on page 187)

(4) Reference is made to the interesting report of L. Silverman and R. A. Davidson on "Collection of Fumes from Ferro-Silicon Furnace Operation." A.I.M.E., meeting, 1954.

Pilot-Plant Studies of a Continuous Slag-Wool Filter for Open-Hearth Fume*†

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Department of Industrial Hygiene
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The problem of cleaning open-hearth furnace gas is one of major importance in the steel industry today. An average 250 ton open-hearth furnace discharges about 25,000 scfm. of gas containing an average particulate loading of 0.4 gr./ft.³ This loading consists of a high percentage of iron fume with particle size less than 5 μ. It can be shown that a collection efficiency of 90 to 95% is required to reduce the effluent to an acceptable amount at ground level[1]. The gas temperatures range from 1400°F. after leaving regenerators (checkers) to 500°F. after leaving the waste heat boiler (if used). Since the product recovered is of little commercial importance, the cost of collection equipment must be kept to an absolute minimum. Presently available dust-collecting equipment will satisfy some of these requirements but not others[1].

With these objectives in mind, the Harvard University School of Public Health sponsored by the American Iron and Steel Institute (Subcommittee on Air Pollution Abatement) has undertaken research into some of the problems of high-temperature gas-cleaning. One phase of this research program has been devoted to investigations into the possibility of using slag wool as a filter for open-hearth furnace fume.

Slag wool is produced from basic blast-furnace slag by melting the crushed slag in a cupola furnace. The molten slag is either impinged on a rapidly rotating disc and "spun" into fibers, or allowed to run into a high-velocity steam jet where it is "blown" into fibers. These are then collected, processed, and bagged as insulating material. Fibers are about 4 μ in diameter with an average length of about 1 in. Our tests have shown that their refractory nature allows them to withstand temperatures of 1000°F. with no apparent deterioration. Cost of these fibers is low, on the order of 1¢/lb. Unfortunately some "shot" (spheres of slag) is usually associated with commercial production of slag wool and must be considered in the above cost. It is possible to obtain wool with longer fibers and less shot if this becomes an important requirement. Previous work on the use of slag wool as a filter material was done during World War II, when investigations were conducted to evaluate its use in personnel protective devices[2].

This report discusses laboratory and field results obtained on slag wool when filtering iron oxide and open-hearth furnace fume.

Laboratory Tests on Slag-Wool Filters

Introduction

Laboratory equipment used to test slag-wool filters [3, 4] consisted of an iron oxide generator, connecting ductwork, a 6-in.-diam. holder for the slag-wool test pad, a flowmeter, and a fan. Iron oxide was generated in the laboratory by 2 different methods. In the first, flake iron powder was injected into the air side of an air-oxygen-acetylene flame where it was oxidized exothermally. In the second, iron carbonyl was burned in an oxygen-acetylene flame to provide more controlled generation. Temperatures at the filter face ranged from 600° to 1200°F. Slag wool for the majority of the test pads was obtained from a local supplier of Baldwin-Hill products. This wool is made by a spinning process from a mixture of iron slag and copper slag. It is a characteristic black color. Standard iron blast-furnace slag was also used for some tests. Physical characteristics of fibers from this slag have been reported[3].

Results

Principal filtration characteristics investigated were filtering velocity, filter packing density and thickness, and method used to make the filter pad. Efficiency and pressure drop were determined for a large number of combinations of filter characteristics. A summary of the results of some of these tests is presented in Table I. Columns 1 and 2 show that filters tested ranged from ½ to 2 in. thick, and were packed to 5 and 10 lb./ft.³ density. Filtering velocities shown in column 4 ranged from 100 to 200 fpm, and associated clean filter resistances ranged from 2.0 to 8.1 in.w.g. as indicated in column 5. These are given at the actual filtering temperature, that is, between 600° and 1200°F. Column 6 indicates the resistance rise (Δp) due to the collection of iron oxide by the filter during the test period (ranging from 10 to 20 min.). The upstream loading of iron oxide (STP) is given in column 7, and the filter efficiency based on iron analysis is shown in column 8. The quantities A and $A/\Delta p$ given in the last two columns, 9 and 10, are explained below.

The resistance of these beds was found to be directly proportional to filtering velocity (up to 200 fpm) at room temperature[3]. Higher temperatures cause an increase in resistance due to an increase in gas viscosity. For example, doubling the absolute temperature (i.e. at about 500°F.) will cause a 70% increase in resistance (resistance is directly proportional to viscosity which, in turn, is proportional to the absolute temperature raised to the three-quarters power). Resistance increased 2 to 14 in.w.g. due to the accumulation of iron fume during filtration.

It was found from these and other laboratory studies that slag wool will collect from 80% to 95% of a very fine iron oxide fume at temperatures up to 1200°F. The efficiency results of Table I indicate generally that collection is by

1. Silverman, L., "Technical Aspects of High Temperature Gas Cleaning for Steel Making Process", *Air Repair*, 4,4 (1955)

* This report is based on work performed under a contract between Harvard University and the American Iron and Steel Institute.

† Presented at the 48th Annual Meeting of the Air Pollution Control Association at Detroit, Michigan, May 23-26, 1955.

2. Rodebush, W. H., "Filtration of Aerosols", Chap. 9 in "Handbook on Aerosols", U. S. Atomic Energy Commission, Washton, D. C., 1950.

3. Silverman, L. and Beauchamp, I. L., "Open Hearth Stack Gas Cleaning Studies — Semi-Annual Report (SA-1), November 1, 1953 to April 30, 1954", Harvard University (Nov. 1954).

4. "Stack Gas Cleaning Studies — Semi-Annual Report (SA-2), May 1, 1954 to October 31, 1954", Harvard University (Approximately Dec., 1955).

TABLE I

Summary of Laboratory Performance of Slag-Wool Filters on Iron Oxide Fume at Temperatures of 600° to 1200°F.

Filter Characteristics			Filtering Velocity, (b) fpm.	Resistance, in. wg.,		Upstream Loading (c) gr./ft.^{3}	Efficiency, %	A %	A / (Δp)
Thickness, in.	Density, lb./ft.^{3}	Method of Mfg. (a)		Initial (b)	Increase, (b) (Δp)				
½	5	H	220	2.2	18.2	0.04	85	4.1	0.22
½	10	H	220	4.4	14.3	0.11	97	3.9	0.28
½	10	H	150	2.7	8.0	0.15	78	3.8	0.81
1	5	H	220	4.0	15.6	0.14	92	4.6	0.28
1	5	H	120	2.0	1.1	0.05	80	0.82	1.2
1	10	H	120	8.1	2.8	0.05	87	0.27	0.14
2	5	H	120	4.0	1.5	0.06	75	0.57	0.30
1	5	SS	120	2.1	4.6	0.13	78	2.5	0.83
1	10	SS	120	7.3	6.6	0.09	94	0.42	0.06
2	5	SS	120	4.7	5.8	0.17	83	1.0	0.22
2	5	AS	110	5.2	8.8	0.29	90	0.70	0.08

(a) Pads made by hand packing (H), slurry agitated by laboratory stirrer (SS), and slurry agitated by compressed air (AS).
(b) At temperatures of 600° to 1200°F.
(c) STP, 70°F. and 760 mm. Hg., Fe_2O_3 assumed from iron analysis.

direct interception (independent of velocity, dependent upon number of targets) and impaction (where separation is directly proportional to velocity). For example, in lines 2 and 3, and 4 and 5, with identical bed characteristics, when the velocity (column 4) is reduced from 220 fpm. to about 135 fpm. the efficiency (column 8) falls from about 95% to about 80%. Thus, higher filtering velocities tend to produce higher efficiencies. This will reduce equipment size but requires more power. Higher packing density producing an increase in efficiency due to an increase in number of targets can be seen by comparing lines 1 and 2, and 5 and 6, where an increase in fiber packing density from 5 to 10 lb./ft.^{3} (other conditions being approximately the same) causes an increase in efficiency from about 82% to about 92%. A change in method of manufacture (column 3) from hand packing (H) to slurry packing (S) seems to produce some change in efficiency as can be seen by comparing lines 5 and 8, 6 and 9, and 7 and 10. The slight advantage shown by the slurry method is probably due to a more uniform fiber dispersion with less likelihood of thin spots in the pad.

The quantity A given in column 9 is defined as the calculated weight gain of the filter[3] due to collected iron oxide, expressed as a percentage of the initial weight of filter material, or pounds of collected material per 100 lb. of slag-wool fiber. When this quantity A is divided by the resistance increase (column 6) during the filtering period (as is done in column 10) it indicates amount of fume a given amount of fiber will collect per inch rise in resistance. If the resistance limits are set, and the average fume emission rate of the furnace is known, this quantity will then indicate how much fiber must be used per unit of time to collect the fume. Higher values of A/Δp mean more fume collected per unit weight of fibers. For example, in line 8 this value is 0.83, which means that on the average 100 lb. of slag-wool fiber will collect 0.83 pounds of iron oxide, per inch of resistance rise. From column 5 it may be seen that the initial resistance of this bed is about 2 in. of water. If the resistance during filtration is allowed to rise to 4 in. of water, then 100 lb. of fiber will collect 1.6 lb. of iron oxide. This suggests that re-use of the fiber as many times as possible is economically desirable.

The results of a laboratory investigation[4] of the possibilities of cleaning and re-using the slag-wool fibers are shown in Table II. The pad of Table II was used to filter iron oxide in the usual way, then removed from the filter holder and

(3) See footnote 3, page 159

(4) See footnote 4, page 159

TABLE II

Laboratory Results on Reslurried Slag-Wool Filter(a) at Temperatures of 600° to 1200°F.

Slurry Number	Resistance, in. wg.,		Upstream Loading, (c) gr./ft.^{3}	Efficiency, %	A %	A / Δp
	Initial (b)	Increase (b) Δp				
1	6.1	11.5	0.50	97	0.70	0.06
2	7.0	6.0	0.23	98	0.85	0.14
3	5.6	7.9	0.14	94	0.44	0.06
4	6.4	5.3	0.11	89	0.32	0.06
5	7.7	4.3	0.16	89	1.20	0.28
6	7.4	10.1	0.09	97	0.60	0.22
7	8.0	11.3	—	—	—	—
8	6.9	13.6	—	—	—	—
9	8.2	11.2	—	—	—	—
10	6.2	11.2	—	—	—	—

(a) Filtering velocity 110 fpm., air-agitated slurry, pad 2 in. thick, packing density 5 lb./ft.^{3}, with 10% new fiber added each time.
(b) At temperatures of 800° to 900°F.
(c) STP, 70°F. and 760 mm. Hg., Fe_2O_3 assumed from iron analysis.

washed in plain water. At this time 10% new fiber was added, and the pad was again formed for another test. This series of operations was continued 10 times, and after each reforming the pad was again tested against iron oxide. At the end of 10 times the pad apparently was still useable, judging from its physical condition. There did not seem to be any consistent increase or decrease in either the initial resistance or the filtering efficiency to indicate that the pad was becoming poorer in performance. This would indicate it is possible to use a given weight of fiber several times. The average efficiency of this reslurried pad was 92%. The average value of $A/\Delta p$ was 0.17. If a 2-in. differential resistance (Δp) is assigned to the filter pad, this indicates that 100 lb. of fiber will collect 0.34 lb. of iron oxide. If it is possible to re-use the material 10 times as shown in Table II, then 100 lb. will collect 3.4 lb. of iron oxide. Since the laboratory iron oxide was not actual open-hearth fume, it became desirable to get field performance data to check the laboratory results.

Field Tests on Slag-Wool Filters Using Laboratory Apparatus and Methods

Cold-Metal Open-Hearth Furnace Fume

Modified laboratory test equipment was set up on the basement level of a 100-ton cold-metal open-hearth furnace[3]. A probe was inserted into the furnace stack below the waste-heat boiler to withdraw furnace-gas samples. Results of this investigation are shown in Table III-A.

The same general conclusions determined from the laboratory studies regarding filtering velocity, packing density and thickness appear to apply to field tests. The efficiency and life factor ($A/\Delta p$) appear to be about the same in the cold-metal furnace and laboratory investigations.

Hot-Metal Open-Hearth Furnace Fume

Since the inlet dust concentrations found in the cold-metal open-hearth study were lower than those reported for general hot-metal open-hearth furnaces, an additional series of tests was run on a hot-metal furnace[4]. The test equipment was set up on the basement level of a 250-ton open-hearth furnace. Samples were withdrawn below the waste-heat boiler. Results of this study are reported in Table III-B. Dust loadings were higher than previously obtained in the cold-metal furnace study. Efficiencies were found to be greater than 90% in most cases. (Lower values reported for 1 in.-5 lb/ft.^{3} pads are thought to be due to peripheral leakage of the gas stream around the fiber pad because of poor edge seal.) Here a consistent trend is found in the life factor ($A/\Delta p$), higher values being associated with less thick or less dense pads. A 1 in. thick pad of 5 lb./ft.^{3} packing density formed by the slurry process (line 5) has a value of 2.5, increased thickness (to 2 in.) lowers the value to 0.91, increased density (to 10 lb./ft.^{3}) decreases the factor to 0.30. This value of 2.5 means that each 100 lb. of slag-wool fiber will collect 2.5 lb. of open-hearth furnace fume/in. resistance rise. If we allow as before, a 2 in. increase in resistance, the fiber then collects 5 lb. of fume. Laboratory studies given above indicate that it may be possible to re-use the fiber 10 times; therefore, each 100 lb. of fiber should collect about 50 lb. of fume. If the average emission rate of a 250-ton furnace (hot metal) is 1 ton of fume/day then it will require about 2 tons of slag wool/day to collect this fume.

After this information had been developed, it was thought desirable to scale up the slag-wool collector process to a higher gas volume and to make the fiber replaceable on a continuous basis.

Field Tests of a Continuous Slag-Wool Filter

Introduction

Laboratory and field investigations reported above have shown that slag wool

(3) See footnote 3, page 159

(4) See footnote 4, page 159

TABLE III

Field-Test Results on Open-Hearth Furnace Fume Using Laboratory Equipment

A. 100-Ton Cold-Metal Furnace

Filter Characteristics			Filtering Velocity, (b) fpm.	Resistance, in.wg.,		Upstream Loading, (c) gr./ft.^{3}	Efficiency %	A %	A Δp
Thickness In.	Density, lb./ft.^{3}	Method of Mfg. (a)		Initial (b)	Increase (b) (Δp)				
1	3	H	100	1.1	7.9	0.079	82	4.7	0.61
1	6	H	100	1.9	14.4	0.063	92	1.9	0.13
1	10	H	100	4.0	7.7	0.030	89	0.65	0.08
2	3	H	110	2.4	1.9	0.024	68	0.42	0.18
2	6	H	95	4.6	2.8	0.011	55	0.08	0.02
2	10	H	100	6.8	4.1	0.017	73	0.14	0.03

B. 250-Ton Hot-Metal Furnace

Filter Characteristics			Filtering Velocity, (b) fpm.	Resistance, in wg.,		Upstream Loading, (c) gr./ft.^{3}		Efficiency, %		Fe_2O_3 % Total	A %	A Δp
Thickness, in.	Density, lb./ft.^{3}	Method of Mfg. (a)		Initial (b)	Increased (b) (Δp)	Total	Fe_2O_3	Total	Fe_2O_3			
1	5	H	85	1.0	5.0	0.18	0.067	71	93	37	11	2.2
1	10	H	70	3.1	8.6	0.21	0.022	92	81	10	2.9	0.35
2	5	H	70	2.5	8.1	0.34	0.053	93	84	16	6.1	0.76
2	10	H	60	5.5	6.3	0.18	0.093	95	95	52	0.69	0.11
1	5	S	85	0.6	2.6	0.11	0.042	40	40	38	5.2	2.5
1	10	S	75	4.4	7.1	0.22	0.039	94	94	18	2.1	0.30
2	5	S	80	1.7	6.0	0.26	0.028	89	96	11	5.1	0.91

(a) Pads made by hand packing (H) and compressed-air-agitated slurry (S).
(b) At temperatures of 400° to 600°F.
(c) STP, 70°F. and 760 mm. Hg., Fe_2O_3 assumed from iron analysis.

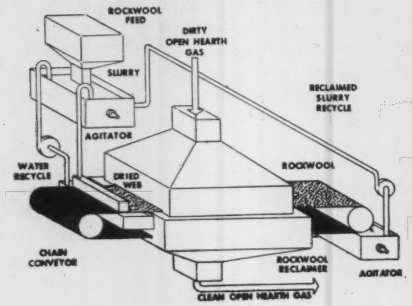

Fig. 1. Schematic Drawing of Continuous Slag Wool Filter

has satisfactory filtering characteristics for open-hearth furnace fume. The test equipment held a stationary 6-in.-diam. pad through which about 20 cfm. of furnace gas was drawn (at 400° to 600°F) for 10 to 20 min. During filtration the resistance increased from 2 to 14 in. above the initial resistance, depending usually upon dust loading and length of test. Since the actual filtration of the furnace effluent would have to be a continuous process closely connected to furnace operation, a filter was constructed in which the filter media could be continually replaced. At the same time, the size of the unit was increased in order to get some idea of over-all operating characteristics and performance. The experimental unit was designed to filter 500 to 1000 cfm. of furnace gas at 800° to 1000°F. at a filtering velocity of 100 to 200 fpm.

Description

An isometric scale drawing showing actual mechanical construction has been presented[5]. A schematic view of the continuous filter is shown in Fig. 1. An endless steel-chain conveyor belt* (2 ft. wide and 3/8 in. pitch) was used as a support for the slag-wool fiber. The belt passed over two 12-in. diam. flat-face pulleys held about 3½ ft. apart in a horizontal plane by a rigid steel frame. Belt tension was maintained by counterweights through sliding shaft bearings at one end. The belt was driven from the opposite end by an electric motor, a gear reducer, and through 2 standard automobile transmissions providing control in linear travel from ½ to 4 in./min. in 5 steps (with reverse). The upper section of the belt passed through a 30-in. long plenum chamber and was supported by five 1½-in.-diam. rollers inside the chamber. Thus a section 2 ft. wide by

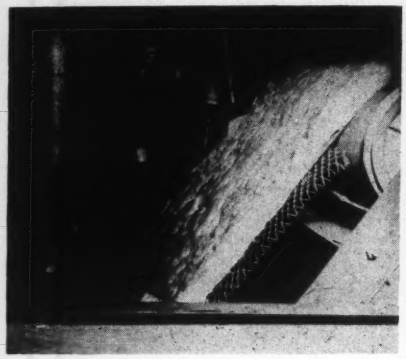

Fig. 2. Slag Wool Web Forming Equipment

2½ ft. long was exposed to the gas stream. A transition was placed on top of the plenum chamber to accomodate an 8-in.-diam. pipe coming from the furnace stack. A hole in the side of the plenum below the belt was fitted with a transition to an 8-in discharge line to the suction side of a fan. Since the belt passed into and out of the plenum chamber while gas was flowing under negative pressure, double end seals were provided to reduce leakage. With the most favorable combination of seals, the majority of the leakage occurred between the woven wires of the belt itself (belt thickness was 5/16 in.).

Continuous webs of slag wool were made as shown in Fig. 2 by drawing the liquid out of a slurry through an endless saran screen (24 in. wide). This belt passed between two 6-in.-diam. pulleys with an idler pulley provided to adjust tension. A suction box (6 in. long x 24 in. wide) was placed directly beneath the belt and connected to a 50 gpm. water pump. The frame holding this assembly was placed into a steel tank (20 in. x 20 in. x 36 in.) so that the suction box was below the water level. The saran screen held back the fibers as the water was withdrawn through the suction box. The formed web emerged at about a 45° angle and passed over rollers down onto the chain conveyor belt and into the gas stream.

Operation

The above equipment was set up on the basement level of the 250-ton hot-metal open-hearth furnace used for tests shown in Table III-B. Fig. 3 shows this setup. An 8-in-diam. pipe comes from a probe in the stack to the top transition of the plenum chamber above the chain belt. Gas from the stack passed through this pipe which contained a stairmand disc (as a flowmeter) and the upstream sampling probe. Fig. 4 shows the gas-discharge side. Here the stack gas passed into the plenum, through the slag-wool filter web and out to the blower through

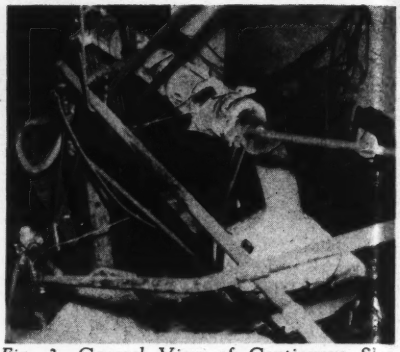

Fig. 3. General View of Continuous Slag Wool Filter As Installed During Field Tests

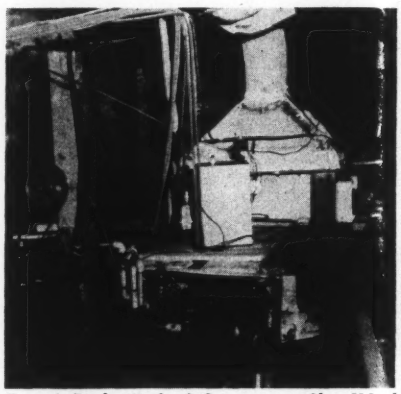

Fig. 4. Right End of Continuous Slag Wool Filter As Installed During Field Tests

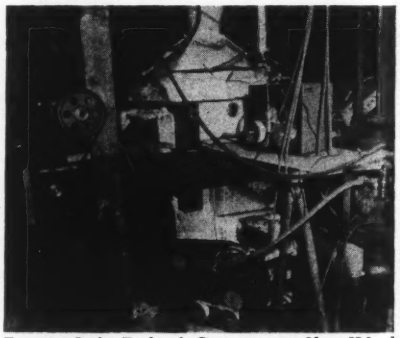

Fig. 5. Left End of Continuous Slag Wool Filter As Installed During Field Tests Showing Sampling Equipment

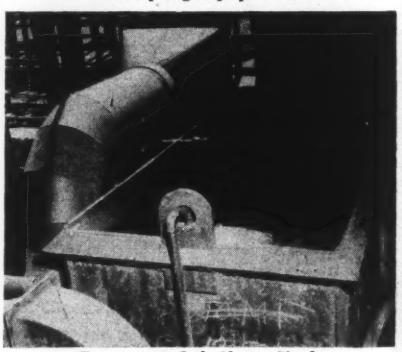

Fig. 6. 300 Gal. Slurry Tank

5. "Stack Gas Cleaning Studies — Semi-Annual Report (SA-3) November 1, 1954 to April 30, 1955", Harvard University (Oct., 1955).

* R-28-30-14, Ashworth Bros., Inc., Worcester, Mass., max. continuous operating temperature recommended, 800°F.

a Venturi flowmeter. The same general area is shown in Fig. 5. Samples of the inlet and effluent dust loading were taken with apparatus shown. The belt drive is shown at the left.

In operation, a 1.5% slurry of slag-wool fiber was made up in the 300 gal. tank shown in Fig. 6. (Other tanks and mechanical agitation were also tried but discontinued). Fiber dispersion was accomplished by bubbling air up through the water from an air manifold at the bottom of the tank. The tank was located on the charging level about 20 ft. above the test filter. The slurry then passed through a 1½-in. pipe (shown in lower right corner of Fig. 6) to the bed-making equipment. Fig. 7 shows the slurry discharging from the end of this line into the bed-forming tank. An associate stood in this area to control the rate of flow of the slurry, and to regulate the amount of suction and the water level in the tank by means of by-pass valves. Water from this operation was discharged to waste sewers, but with a suitable liquid filter could have been recirculated to the tank above. As the web formed on the saran belt, the operator slowly rotated the top pulley by hand to remove it from the liquid. Due to the porous nature of this web it generally dewatered readily while slowly advancing up the inclined belt. Some difficulty with insufficient dewatering was experienced and additional dry suction could have been provided.

The continuous filter web then passed down onto the slowly moving chain conveyor and then through the gas stream. Used material coming out of the gas

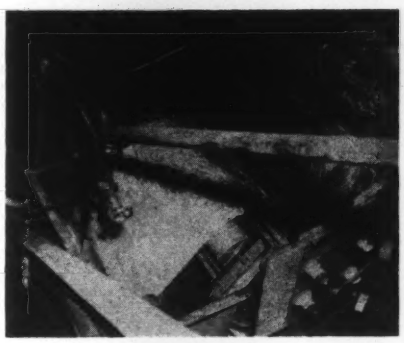

Fig. 7. General View of Slag Wool Web Forming Equipment During Operation

stream (Fig. 5) fell off the conveyor into a wooden box. Periodically this material was carried upstairs by hand, washed, and re-used (on a batch basis).

Sampling and Analysis

During extended periods of operation 2 types of particulate samples were obtained. The inlet and outlet probes have been described elsewhere[3]. They held 1 9/16-in.-diam. circles of 1106B* all-glass paper. These circles had been previously weighed in the laboratory and were reweighed after the sample had been collected. Knowing the sampling rate and total sample time (and in the case of the downstream sample, the amount of leakage air drawn in) it was possible to calculate total dust loading and total weight efficiency. These samples were then chemically analyzed for iron by a colorimetric technique[3]. Iron loading and efficiency data, and iron to total solids ratio in the stack gas were calculated from this information. For repetitive loading and efficiency information 2 AISI* air-pollution samplers were modified to draw 0.5 scfm. by critical flow orifices and air ejectors. Samples were withdrawn from a side arm of the same probes as previously used. By interconnecting the upstream and downstream AISI samplers it was possible to run them from one cam in cycles of 5 min. sampling and 1 min. off for tape travel. The tape used was made of 1106B all-glass paper. These samples were chemically analyzed for iron only.

A continuous pressure recorder was also used to indicate the pressure loss across the filter bed during operation.

Results

A total of 23 continuous filter tests ranging from ½ to 3 hr. were made with this equipment, including all parts of the furnace cycle or "heat": making bottom (empty), charging scrap, meltdown, pouring hot metal, ore boil, lime boil, working period, carbon makeup or decarb, and tapping. Two different types of slag wool were employed to form experimental webs. The first was that used for the majority of laboratory studies ("black") and the second was that supplied by the slag-wool plant at the steel making installation where the test unit was set up. Summarized results of this study are presented in Table IV.

The filter-web characteristics are shown in the first 3 columns, and the average filtering velocity and resistance

[3] See footnote 3, page 159

* Mine Safety Appliance Co., Pittsburgh, Pa.

* Research Appliance Co., Pittsburgh, Pa.

TABLE IV

Summary of Field-Test Results on Continuous Slag-Wool Filter

Filter Characteristics			Filtering Velocity, (b) fpm.	Average Resist. (b) in. wg.	Upstream Loading, (c) gr./ft.³		Efficiency, %		Fe_2O_3 Total Upstream %	Bed Travel Rate, in./min.	Oper. Time, Min.	Furnace Cycle (d)	Remarks (e)
Thickness, in.	Density, lb./ft.³	Source (a)			Total	Fe_2O_3	Total	Fe_2O_3					
1	5.6	B	100	4.3	0.10	0.041	50	52	—	1	176	O,L,W,	1P.
1	6.8	"	90	4.5	0.094	0.048	48	53	41	3	154	L,W	2P.
1	5.6	"	90	4.2	—	0.025	—	52	51	2	193	T,E;C,M,H,O	1P.
1	6.8	"	60	5.0	—	0.048	—	64	—	3	110	L,W	2P.
¾	8.6	J	90	4.5	—	0.026	—	42	—	1	97	W	1P.
¾	9.1	"	90	4.8	0.060	0.021	51	38	35	2	87	E-W	2P.
¾	9.2	"	75	5.4	0.094	0.039	59	63	42	2	42	O	3P.
¾	8.4	"	65	5.7	0.068	0.027	60	75	40	2	35	L,W	4P.
¾	6.6	"	95	4.0	0.11	0.027	49	58	25	4	80	XD,W	2P.
¾	8.1	"	80	4.3	0.11	0.039	44	65	36	2	164	M,H,O,L	1P.
1	7.5	"	70	5.7	0.12	0.042	66	64	35	2	111	C,M	2P.
¾	6.4	"	80	4.9	0.083	0.025	31	61	30	1	69	M	3P.
1	7.3	"	50	6.2	0.25	0.082	89	73	33	3	28	W	4P.
1	3.9	B	100	3.9	0.17	0.050	52	54	29	4	119	M,H	1P.
¾	4.0	"	95	4.7	0.074	0.036	52	68	49	1	95	H,O	2P.

(a) Wool manufactured by Bethlehem Steel Co., "Mineralite" (B), and Baldwin-Hill Co., "B-H Spun Mineral Wool" (J).
(b) At temperatures of 400° to 700°F.
(c) STP, 70°F. and 760 mm. Hg., Fe_2O_3 assumed from iron analysis.
(d) Furnace cycle (heat) consists of phases: empty, making bottom (E); charging scrap, ore, and limesto ne (C); melt down (M); pouring hot metal (H); ore boil (O); lime boil (L); working (W); extra decarburization (XD) or extra carbon makeup (XC) ; and finally, tapping (T).
(e) Indicates the number of uses or "passes" of a given amount of slag wool.

(at temperatures of 500° to 700°F.) are given in columns 4 and 5. The average inlet dust loading based on total weight and iron anaysis is given in columns 6 and 7. Total and iron oxide filter efficiences are reported in columns 8 and 9. The percentage of iron oxide (assumed Fe_2O_3 calculated from iron analysis) to total solids is given in column 10. The average bed travel rate, total operating time, and part of furnace production cycle are shown in columns 11, 12, and 13, respectively. The "Remarks" column shows the number of times the fiber was used. Each test in Table IV consists of one full passage of a certain amount of slag-wool fiber through the filter unit. At the end of the test the fiber was washed, about 10% new fiber was added, and the batch was then re-used. In lines 1 and 2, 3 and 4, and 14 and 15, operating performance for the first two passes of B fiber are reported. At about 0.1 gr./ft.^{3} the average efficiency is near 50%. The first pass seemed to give lower resistance and higher filtering velocity than the second pass. Lines 5 through 8 and 10 through 13 show the performance of "J" fiber on 4 separate passes. The first group (5 to 8) shows a consistent decrease in filtering velocity and increase in resistance. There is a corresponding increase in efficiency from about 40% to 70%. The second group (10 to 13) shows approximately the same trends as the first with the exception of line 12, where the filtering velocity rises to nearly the original value, and the resistance is low. The average inlet loading is lower in this group (melting scrap) than that of the other three tests, which would account for this apparent discrepancy. With the exception of line 12, the efficiency increases steadily as filter resistance rises.

The fiber from the last test (line 15) was run through the system in small batches (without special washing) with 12½% new fiber added. This test is shown in Table V. Based on the time to run the batch (20 min.) and the original weight of fiber, it was estimated that the fiber was used 8 times. Data presented in Table V, while not directly comparable to tests shown in Table IV, indicate the variability of the results due to variations in the dust loading and the bed-forming process.

Discussion

Particle Size. Samples for particle-size analysis were obtained before and after the waste-heat boiler. Stack gas was withdrawn through a glass electrostatic precipitator, and particulate material was deposited on electron microscope targets held in a special holder[3]. The mass median diameter before the waste-heat boiler (at the location of test equipment) was found to be 0.65 μ (count median diameter 0.047μ). After the waste-heat boiler the mass median diameter was found to be 0.82 μ (count median diameter 0.057 μ). It is reasonable to conclude that there is some particulate agglomeration due to the passage of the gas through the waste-heat boiler and the I.D. fan. Location of the continuous slag-wool filter before the waste-heat boiler represents the worst possible study case from the standpoint of both particle size and temperature. Collection equipment placed after the boiler would operate on a larger particle size and at a lower gas temperature.

Inlet Loading. Inlet dust loading to the filter varied with the furnace operation. Low loadings (0.05 gr./ft.^{3}) occurred during melt down, working period, while tapping, and with the furnace empty (making bottom). Higher loadings (0.15 gr./ft.^{3}) generally occurred during the pouring of hot metal, the ore boil, the lime boil, part of the working period, and at make-up or decarburization (if required, at end of working period).

The average total inlet loading was found to be 0.1 gr./ft.^{3} (STP), containing about 35% iron oxide (assumed Fe_2O_3). The maximum value found was 0.25 gr./ft.^{3}, occurring 3 separate times, twice during the addition of hot metal and once during a carbon make-up (with hot metal). Since these values are lower than those reported for other producers (0.4 average, 1.0 at hot metal) either one or both of two factors may be the

(3) See footnote 3, page 159

TABLE V

Continuous Slag-Wool Filter Test, with Recycled Fiber Plus 12½% New Fiber

Filter Characteristics(a)		Filtering Velocity,(b) fpm.	Temp., °F.	Time, Min.	Resistance,(b) in. wg.		Upstream Loading,(c) gr./ft.^{3}		Efficiency, %		Fe_2O_3 Total Upstream %	Bed Travel Rate, in./min.	Remarks(d)
Thickness, in.	Density, lb./ft.^{3}				Initial	Final	Total	Fe_2O_3	Total	Fe_2O_3			
1	4.5	115	550	15	4.2	4.8	0.093	0.040	75	80	43	2	Charge completed start melt down. 3P
1	4.3	95	610	42	4.0	3.9	—	0.027	—	67	—	2	3P
							—	0.029	—	71	—	2	3P
1	3.3						—	0.024	—	66	—	2	3P
							—	0.023	—	55	—	2	4P
1	3.5						—	0.027	—	57	—	3	4P
½	5.0						—	0.020	—	29	—	3	4P
							—	0.019	—	10	—	3	4P
1	7.1	75	650	27	3.5	3.0	—	—	—	—	—	3	Pouring hot metal 5P
¾	5.1	95	650	37	10.8	5.6	—	0.013	—	23	—	3	Ore boil 6P
							—	0.011	—	10	—	3	6P
							—	0.011	—	11	—	3	7P
¾	7.0	110	710	18	6.2	4.9	—	—	—	—	—	3	7P
1	5.2	110	715	10	4.7	5.6	0.067	0.022	42	62	33	3	8P
¾	5.3	100	—	149	6.6	4.6	0.080	0.022	59	46	27	3	Average for whole test

(a) Bethlehem "Mineralite" spun wool.
(b) At temperature shown in column 4.
(c) STP, 70°F. and 760 mm. Hg., Fe_2O_3 assumed from iron analysis.
(d) Indicates part of furnace cycle (heat) occurring during test: also approximate number of times fiber had passed through filter unit.

cause. First, the gas velocity at the probe in the stack may not have been isokinetic; or second, the dust loading may not have been uniform across the stack, and not representative at the sampling point. No velocity or dust-loading determinations were made at the sampling point.

Since the loadings are lower than expected, it is reasonable to assume that the particle size may be smaller than that based on the average loading. It is reasonable to conclude that efficiency and resistance results based on these loadings may be conservative.

Resistance. Filter resistance during operation was controlled by the rate of filter-web travel. The inlet dust loading to the filter varied with the furnace operation. It was found that with low dust loadings (during melt down, working, tapping, and with the furnace empty) it was possible to maintain low resistance (4 in.w.g.) with the slower web travel rates (½ to 1 in./min.). During the higher loadings (occurred during the pouring of hot metal, the ore boil, the lime boil, part of the working period, and make-up or decarb.) the bed travel rate was generally advanced (to 2 to 4 in./min.) to maintain low resistance. These changes in speed associated with furnace production can be seen in Table IV (columns 11 and 13), in lines 5 and 10, and 6 and 9, where the fiber condition is approximately the same. Line 5 shows that during the working period it was possible to operate at 1 in./min., but in line 10, during the hot-metal addition and the reactions immediately following, 2 in./min. was really not fast enough for control (80 fpm. being lower than the desired 100 fpm.). The same comparison may be made in lines 6 and 9, line 9 being a period of ore-limestone decarburization requiring high travel rate (4 in./min.) compared to the empty and working period covered during test in line 6 (at 2 in./min.).

Due to the experimental aspect of the bed-forming process, it was not always possible to run as fast as furnace conditions might require, so that this factor is reflected in lower filtering velocities and higher resistances than would be the case with automatic bed forming and bed travel by resistance control.

Efficiency. An examination of the data presented in Table V indicates that efficiency ranged from 10 to 80%. This variation also occurs in tests presented in Table IV, where collection of efficiencies range from 40 to 90% with an average near 60%. Various mechanical modifications in seals were used to prevent leakage of the stack gas by the sides of the filter. Occasional cracks, holes, and disturbances in the filter web itself were unavoidable, and attempts were made to patch these as the process continued, with some success. It is believed that these 2 factors contributed to reduced efficiency.

Since the degree of cleaning achieved in the experimental pilot unit depended upon several mechanical factors incorporated into the design and operation, collection efficiencies reported reflect the "efficiency" of the mechanical design as well as fiber-bed efficiency. For this reason, the collection efficiencies reported are felt to be very conservative (since they are lower than expected and required) and should be substantially increased by proper redesign and reconstruction of the unit based on the field experience. If the fiber bed will collect 90%, but the holder allows gas to bypass, or if the bed has discontinuities, then the over-all filter-unit efficiency will be considerably lowered. Redesign and reconstruction are under consideration at present. Location of the pilot unit below the waste-heat boiler also represents the least favorable condition for particle size and gas temperature.

Gas temperature. The gas temperatures at the filter bed ranged from 500° to 700°F. Stack temperature at the probe was about 1400°F. The difference was primarily due to the thermal capacity of the system and the large amount of surface area available for heat loss. Thermal insulation was applied to the inlet duct and the top surfaces of the test unit, and contributed to a higher temperature at the filter.

Sulfur Gas. Two methods of determining sulfur in the stack gas indicated concentrations near 100 ppm. (as SO_2). The presence of sulfur gases is felt to contribute to fiber attrition. Laboratory studies have shown this to be a factor and additional investigations of this problem are being considered.

There is some indication that an appreciable amount of sulfur is removed on and in the bed, as acid or SO_3, particularly when the fibers are damp. The possibilities of reducing sulfur gas concentrations by this method will be investigated.

Packing density. Web densities and thicknesses shown in Tables IV and V were calculated from samples taken at regular intervals from the used web as it emerged from the plenum. These figures therefore reflect the original packing density plus a slight increase due to the weight of accumulated material. This increase due to captured material was shown to be about 5% for 1 in-5 lb./ft.^{3} webs when filtering hot-metal open-hearth fume. Packing densities shown in Table V vary from 3.3 to 7.1 lb./ft.^{3}, with high values occurring when large amounts of particulate material are being discharged from the furnace. The average clean-fiber packing density during this test probably ranged from 3.3 to 5.0 lb./ft.^{3} with the 2 high values (7.0, 7.1) shown probably being due to the accumulation of a large amount of large particles on the web.

Changes in bed density from test to test reflect the several factors involved in the method used to form the bed, plus the physical condition of the fiber itself. The majority of the webs shown in Table IV (except the last two) were made by drawing the fiber onto the saran screen over the suction box and then smoothing the upper surface of the web with a gentle hand pressure. This additional pressure was enough to increase the web density by a factor of 2 or 3. Test webs shown in the last 2 lines of Table IV and in Table V were formed by the applied suction only, without any attempt to form a smooth surface. The latter procedure proved to be more desirable.

Minimum density obtained by the second forming method was approximately 2.5 lb./ft.^{3} It should therefore be

It should therefore be possible by the application of light pressure to vary the bed density at the time of forming between 2.5 and 9 lb/ft^3, or higher if desired for any reason.

Life Factor. By assuming the average inlet loading to be 0.1 gr./ft.^{3}, filtering velocity 100 fpm., web thickness 1 in., density 5 lb./ft.^{3}, travel speed 1 in./min., efficiency 80%, and a gas temperature of 625°F., the life factor (A) can be calculated to be 4.3%. Based on fiber replacement of 12.5%, or 8 lives, the factor becomes 34%, or 34 lb. of fume/100 lb. of fiber. With an emission rate of 2500 gr./min., a filter of this type for this furnace would require about 1500 lb. of fiber/day. If the effluent is 0.4 gr./ft.^{3} and the belt travel speed is increased to 4 in./min., filter requirements increase to 6000 lb./day. A conservative estimate of slag-wool requirements for a 250-ton hot-metal open-hearth furnace therefore ranges from 1 to 3 tons/day.

It has been shown that the life factor with fume generated in the laboratory is about 3.4 lb./100 lb. of fiber, for a 2 in.-5 lb./ft.^{3} pad re-used 10 times. Examination of the variation of life factor with filter thickness (as discussed for data of Table III-B) indicates a proportionally larger gain in weight for a thinner pad. A 1 in.-5lb./ft.^{3} pad would therefore be expected to recover (on the basis of 10 passes) about 9.5 lb./100 lb. of fiber.

The difference between 9.5 obtained in the laboratory and 34 calculated from the field data is attributed to the difference in particle size of the laboratory and field aerosols. The finer particle size of the laboratory fume (count median diameter 0.027 μ) would be expected to cause higher resistance/unit weight of collected material.

Conclusions

1. Laboratory and field tests of various types of slag-wool-fiber test pads and continuous webs indicate that efficiency can reasonably be expected to exceed 90% with moderate filter resistances at filtering velocities of 100 fpm., and at temperatures up to 1200°F.

2. Various mechanical defects in the experimental pilot unit which tended to lower collection efficiency can be eliminated by proper design and construction.

3. Resistance of the filter can be controlled between 2 and 4 in. of water by variations in web speed coordinated with furnace production cycle.

4. Web packing density and thickness can be controlled at the point of formation by suitable design.

5. By washing and re-using the slag-wool fibers about 8 times, it is estimated that 100 lb. of fiber will collect about 30 lb. of furnace fume, and it is estimated that the "average" 250-ton open-hearth furnace would require about 3 tons of fiber/day for gas-cleaning.

6. Average dust loading determined from field tests was about 0.1 gr./ft.^{3} which is believed to be lower than can be expected due to location of filter sampling probe. Higher loadings should contribute proportionally greater amounts of larger particles, which indicates that average efficiency results may be somewhat conservative.

7. By particle-size analysis (electron microscope samples) it was found that the mass median particle size before the waste-heat boiler is 0.65 μ and is 0.82 μ after the waste-heat boiler. Temperatures before and after the waste-heat boiler were 1400° and 600°F. respectively. Some difference in particle size before and after the waste-heat boiler would appear to indicate that some thermal agglomeration is occurring. Collection of fume after the waste-heat boiler should be more effective due to this increased particle size.

8. Additional mechanical design to permit continuous handling and washing of the slag-wool fibers is required to make the experimental pilot unit completely automatic. Web-forming and slurry-processing equipment must be installed to operate as required by resistance controls. This is primarily a laboratory project and will be considered.

Summary

This report includes laboratory investigations of the resistance and efficiency of commercial spun-slag wool fibers used to filter iron oxide contained in a high-temperature gas stream (600° to 1200°F). Field tests of a continuous web of slag-wool fibers used to filter open-hearth furnace fume at temperatures from 400° to 700°F. are also reported. Filtration velocity in both studies averaged about 100 ft./min.

Laboratory studies indicate that collection efficiencies over 90% may be obtained with 1-in. thick pads of slag wool packed to 5 and 10 lb./ft.^{3} density. Resistances initially range from 2 to 8 in. of water, and increase 2 to 14 in. during filtration of 0.1 gr./ft.^{3} of a fine iron oxide aerosol.

Field studies of a continuous web of slag wool showed variations in efficiency from 10 to 90%. Filter resistance was maintained near 4 in. of water during operating periods ranging from ½ to 3 hrs. A correlation between inlet fume loading and furnace production was observed which influenced filter requirements. Mechanical factors in the test unit tending to lower the efficiency of the continuous web were determined, and suitable redesign may be expected to eliminate these faults.

Based on field studies, it was found that an average 250-ton hot-metal open-hearth furnace would require 1 to 3 tons of slag wool/day to filter stack gas.

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Olfactometry: Its Techniques and Apparatus*

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The subject of the measurement and control of odors, for use in laboratory research and industrial studies, has gained importance within the last few decades. The purpose of this paper is to describe the apparatus and techniques used in the past and to describe a new olfactometer developed after 6 years of experimentation. Some facts concerning the techniques concerned with odor measurement are also advanced to aid those interested in the subject.

Odor-Measurement Devices

Olfactometry presents many difficult problems to an investigator desiring to begin a research problem employing thresholds for expression of odor intensity, because of the very nature of the olfactometers and odorimeters in use today. There are numerous instruments for determining the intensity or presence of odors, e.g., Odorimeter, Osmoscope, Olfactometer, Olfactoscope, etc., but each measures in units different from another, and each employs a different principle with differing variables affecting the odor dilution.

Considering a few of the available odor-measuring devices in use today (for examples of the variables involved in odorimetry or olfactometry) we may cite the Allison and Katz[1] Odorimeter as an example of the larger-type apparatus, while illustrations of small-type apparatus are the Zwaardemaker Olfactometer[2], the Fair-Wells Osmoscope[3], the Foster-Smith-Scofield Olfactory Stimulator[4], and the Elsberg-Levy Olfactometer[5,6]. These are only a few of the many types of odor-measuring devices and techniques, and further references[7,8,9] should be made to see the various devices used for this purpose.

The principle of most of the presently used measuring devices involves the confinement of an odorous material in some type of container, the passing of air into this space, diluting, and then directing the odorivector to an observer for judgment. In the particular case of the Allison and Katz Odorimeter, a flow of purified air is "passed at a uniform rate through or over the chemical, and this air then mixed with another measured volume of pure air also flowing at a uniform rate."[1] This type of measuring device is complex because of the number of Venturi-type flow meters used and their necessary adjustment for varying the concentration of odorivector delivered to the observer. However, for the odor-threshold measurements made by Allison and Katz, there was no demand for a rapidly adjustable odorivector. Calculations of the concentrations of odors presented to the subject were made from the loss of weight of the odorous liquid at certain flow settings.

The Zwaardemaker Olfactometer is constructed on the principle of exposing a cylindrical, calibrated, variable, adsorptive surface over an inner tube, one end of which is exposed to the air and variable surface while the other end leads directly into the nostril of an observer. The variable surface is an adsorbent for the odoriferous substance and the amount of surface exposed over the inner tube, for production of a perceptible odor, is the direct measure of odor intensity for a substance.

The Elsberg-Levy method of odor measurement[6] fundamentally involves the use of a bottle fitted with a hypodermic syringe and a pair of glass-tube carriers leading to the observer. A certain amount of odorous substance is placed in the bottle and its vapor allowed to reach equilibrium with the contained air. After the air above the odorous substance is saturated for a particular temperature and pressure, a measured volume of odorivector is presented to the observer in the form of a "blast" of odor-carrying air. This method of presentation of a test odor to a subject was named the "blast-injection technique."

A similar type of device was used by Foster, Smith and Scofield[4]. However, the bottle containing the odorant did not have a syringe for stimulation purposes. The observer inhaled through 2 glass stimulators held securely in the nostrils, and this caused the atmospheric air to become saturated with odorivector as it bubbled through the liquid to be inhaled in vapor form.

The Checkovich-Turner Osmometer (Fig. 1) is a static-type unit, employing 2 calibrated air-pressure chambers which are attached to a manometer recording pressure within one or both cylinders. Odorless air is charged into one or both cylinders at a measured pressure, and is then gradually bled into a flask containing saturated vapor above the test material. Thus, a certain known amount of odorless air is used to replace a similar quantity of saturated odorivector in 2 l. erlenmeyer flasks. The flasks are immediately covered with a watch glass after charging and the contents allowed to thoroughly diffuse. A number of such flasks (each containing different dilutions of an odorivector) are thus made, and subjects are asked to judge the dilution at which an odor is perceived.

The Fair-Wells Osmoscope[3,10] is a model of simplicity and compactness having 2 brass telescoping tubes. Along the

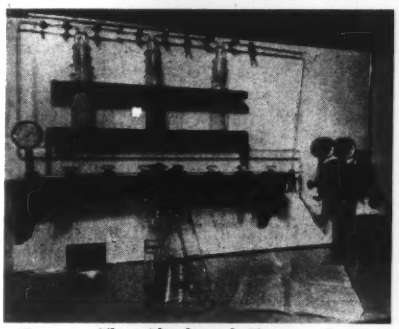

Fig. 1. The Checkovich-Turner Osmometer

* Presented at the 48th Annual Meeting of the Air Pollution Control Association at Detroit, Michigan, May 22-26, 1955.

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(2) Zwaardemaker, H., *Fortschritte der Medicin*, **19**, 721-31 (1889).

(3) "Odor Determinations on a Numerical Basis . . . The Fair-Wells Osmoscopes," Bul. No. **524**, Eimer & Amend, New York, N. Y.

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(10) Fair, G. M., and Wells, W. F., "The Air-Dilution Method of Odor Determination in Water Analysis," *J. Amer. Water Works Assoc.*, **26**, 1670-77 (1934).

middle section of the inner tube there are specially arranged holes, which are closed or opened by adjusting the outer tube, likewise bored along its middle section with holes. The inner tube serves as the major route of the odor to be tested. A subject inserts special nose pieces on one end of the tube into each nare. The opposite end of the tube is inserted into the odorous test environment. The outer tube is rotated and moved to progressively open and close holes, allowing fresh (supposedly odorless) air to dilute the odor traveling the inner tube with each inhalation of the subject. The subject and the body of the osmoscope, except the end inserted in the odor source, should be in a relatively odor-free environment to insure proper fresh-air dilution of the odor being tested.

Mention should be made here of the indirect method of Ramsey[11] in determining differential odor "Thresholds" between odorous substances. Ramsey saturated a cotton pad with the odoriferous substance and this pad was affixed to one end of a long glass tube. The observer was at the other end and waited until he could smell the odor. This type of arrangement really measured the rate of diffusion of an odor vapor along the tube, but allowed a crude determination of different rates of diffusion for various substances and thus an indirect measure of differences in odor intensity.

When odor-threshold measurements are made with devices such as the Zwaardemaker Olfactometer, the Fair-Wells Osmoscope, the Ramsey tube-diffusion technique, or any other device having an open environment (odorous material not completely sealed in a self-contained unit), many variables affect the measurement, e.g., temperature, humidity, atmospheric pressure, air currents, and environmental contaminants. No doubt the principle involved in the Fair-Wells Osmoscope enables the determination of differences in odor intensities of various substances, but even if the odorivector end of the Osmoscope is placed in a controlled environment, a variable is introduced by the air for dilution. Threshold measurements obtained from such devices can only be approximations of the weight of the substance per unit volume of air.

The Allison-Katz Odorimeter can deliver, from a self-contained unit, a controlled odorivector to an observer. This is a device where temperature, pressure, flow of odorivector, and the purity of dilutent air can be known. The only real variable unaccounted for is the environment in which the subject or observer sits.[12]

These devices illustrate some of the apparatus used today in olfactometry. Basically, all of them can be classified according to the principle employed to achieve variable odor dilution. Organaleptic olfactory measuring devices, with representative examples, are outlined according to principle of operation in the following section. There are, of course, other odor-measurement techniques not requiring the nose which can be utilized in olfactometry, and they are outlined in the second following section.

Organaleptic Odor-Measurement Devices

Devices which deliver variable concentrations of odorants to human subjects for subjective appraisal are classified as follows:

A. *Vapor Dilution Method*

The saturated vapor of an odorous substance is utilized by some method to produce test dilutions of that odor for human appraisal.

1. *Static Method.* The saturated vapor is removed in part, or in total, into another flask or unit for static dilution, or where the subject has a limited number of set dilutions to appraise:
   a. The Checkovich-Turner Osmometer
   b. The Barail Osmometer[13]
   c. The Elsberg-Levy Olfactometer
   d. The Fair-Wells Osmoscope

2. *Continuous Method.* Same as above, except that the saturated vapor is incrementally removed from a controlled environment and bled continuously into a variable, diluent air stream:
   a. Allison-Katz Odorimeter
   b. Zwaardemaker Olfactometer
   c. Procter & Gamble Osmo[14]

3. *Variations of Above—Volatilization Technique.* The test material is enclosed in a space of known volume, and allowed to volatilize completely:
   a. Flask Dilution Technique[8]
   b. Enclosed Sniff-Blotter Technique

B. *Vapor Adsorption and Breakthrough Method*

Apparatus constructed around the novel principle of introducing a variable-flow odor vapor into an adsorbent column of known volume, and measuring by smell the time required for "breakthrough" of the odorant as in the Moncrieff Adsorption Unit[15].

C. *Liquid Dilution Method*

1. An odorless solvent is used to dilute the odorous material in an enclosed space, and fractions of the vapor are removed for human appraisal:
   a. Elsberg-Levy Olfactometer
   b. Foster-Smith-Scofield Stimulator

2. As above, except odor appraisals are made directly from the mouth of an open flask or sniff bottle, and without proportionating devices, as in the flask dilution technique:

D. *Rate of Diffusion Method*

The odorous material is placed in or on an adsorptive surface and at the end of a diffuser column which encloses odorless static air. Rates of diffusion times are measured (judged) by 2 methods:

1. *Set Length Columns.* A standard length tube is employed, where the odorant is placed at one end and allowed to diffuse the length of the tube until a subject, at the other end, first perceives the odor, as in the Ramsey Unit.

2. *Variable Length Columns.* Same as above, except that sniff ports are provided to observe differential layering (or travel) of odorant or its intensity at various levels as a function of time, as in the Snell Laboratory-Air Force Unit.[16]

Odor-Measurement Methods Not Employing the Human Nose

The following methods of odor detection or measurement are not based on the human sense of smell.

A. *Chemical Methods*

Chemical methods based on the use of chemical agents (oxidants) to indirectly measure the amount of odorous material in certain environments (where rate of reduction of oxidant is in some way related to perceptible odor levels) include the following:
   a. The Kuehner Apparatus[17]
   b. The Lang-Farber-Yerman "Stinkometer"[18]

B. *Physical Methods*

Physical methods may be based on surface effects resulting from the absorption or adsorption of odorous substances. Surface phenomena of solids and liquids, be it changes in surface tension or modification of certain electrical potentials, may serve as criteria of the presence or

(8) See footnote 8, page 170

(11) Ramsey, W., *Nature*, **26**, 187 (1882).

(12) Foster, D., Scofield, E. H., and Dallenbach, K. M., "An Olfactorium," *Am. J. Psychol.*, **63**, 431-40 (1950).

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(14) Gex, V. E., and Snyder, J. P., "New Device, Wider Concept Helps to Measure Odors Quantitatively," *Chem. Engr.*, **59**, No. 12, 200-201+ (1952).

(15) Moncrieff, R. W., "The Characterization of Odors," *J. Physiol.*, **125**, 453-65 (1954).

(16) Gee, A. Haldane, "Organoleptic Appraisal of Three Component Mixtures," ASTM Reprint **105b**, p. 5, 1954.

(17) Kuehner, R. L., "The Validity of Practical Odor Measurement Methods," *Ann. N. Y. Acad. Sci.*, **58**, No. 2, 175-86 (1954).

(18) Lang, O. W., Farber, L., and Yerman, F., "The Stinkometer," *Food Ind.*, **17**, No. 8-9, 116, 118 (1945).

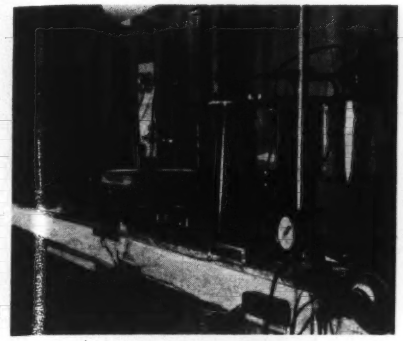

Fig 2. The Mateson Olfactometer, overall view of odor unit, air purification unit, and constant-temperature apparatus

absence of odors. The Purdue pendant drop method of surface tension measurement[19,20] may be cited as an example.

C. *Indirect Biological Methods*

Insects may be used in specially constructed "olfactometers", or cages, to respond to odors. Large insect populations are used for each test; thus, statistical reliability can be very high. The Dethier-Yost Insect Olfactometer[21] may be cited as an example.

Instrumentation Difficulties

To completely review each odor-metering device and technique is beyond the scope of this paper. Attention is called to the fact that none of the existing "olfactometers" can be considered a standard instrument for use in odor studies. Further, it can be stated that experimental data obtained from the various instruments prevent correlation of their various expressions of measurement.

Because of this lack of standard instrumentation in the odor field, there is no standard way of expressing odor concentrations, or determinations, from one instrument to another. Thus, a problem of some magnitude is met when using devices similar to that of the Elsberg and Levy method of measuring olfaction, because of the difficulty, or impossibility, of determining the threshold values for quantitative expression in weight/volume units, which all significant olfactory research problems must begin with. Units like the olfactie or the "olfactory coefficient" (Elsberg), are probably acceptable for use in some types of olfactory research problems, but these units of comparison do not, or cannot, be significantly correlated with the very minute concentrations of odor vapor required to arouse the olfactory cells. They are large and clumsy when compared with the mg./l. concentrations used by Dalla Valla[22] and McCord[9]. If there were an error of only one specially scaled unit (e.g., olfactie), it may really represent a gross error in the quantitative units needed for accurate work in the investigation of olfaction.

(19) Tanyolac, N. N. and Eaton, J. R., "Study of Odors," *J. Am. Pharm. Assoc.*, Sci. Ed., **39**, No. 10, 565-74 (1950).

(20) Eaton, J. R., Christian, J. E., and Campbell, J. A., "Surface Phenomena Related to Odor Measurements," *Ann. N. Y. Acad. Sci.*, **58**, No. 2, 239-49 (1954).

(21) Dethier, V. G., and Yost, M. T., "Olfactory Stimulation of Blowflies by Homologous Alcohols," *J. Gen. Physiol.*, **35**, 823-39 (1952).

Fig. 3. The Mateson Olfactometer, the odor saturation and mixing unit

A New Olfactometer

Due to the fact that serious work on odors was hampered by the lack of suitable apparatus, the author began the construction of an olfactometer in 1950 while at the University of Texas. The objectives were to construct a research tool with the following characteristics:

1. Simple operation and maintenance.
2. Provision for adequate knowledge and control of temperature, pressure, and humidity of the odorivector at all times.
3. Provision for the expression of odor concentrations according to weight/volume quantities.
4. Provision for continuous variance of the concentration of the odorivector.
5. Adaptable to any type of odorant, solid or liquid, of high or low vapor pressure, and of any intensity.
6. Continuous operation during an experiment on an odorant, so that breakdown is avoided for clearing between each determination.
7. Adaptable to reliable threshold determinations on pure chemicals or to complex odor mixture studies.

With the expert guidance of Dr. Karl M. Dallenbach, of the University of Texas, a suitable olfactometer was developed which fulfilled most of our objectives. Fig. 2 and 3 show the Mateson Olfactometer, as developed at the University of Texas.

(22) Dalla Valle, J. M., and Dudley, H. C., "Evaluation of Odor Nuisances in the Manufacture of Kraft Paper," *U. S. Pub. Health Repts.*, **54**, 35-43 (1939).

Fig. 4. The Mateson Multi-Stimulus Olfactometer. The unit is set up to test the deoderant capabilities of a new deoderant product vs. the deoderant capabilitiy of an adsorbent bed on a controlled malodor.

Some Considerations Regarding Thresholds of Odors

A research program was initiated with this apparatus to determine the effects of variable temperature, pressure, humidity, time, stimulus presentation, etc., on threshold concentrations. Pure chemicals were used, and suitable subjects were trained to participate in the tests. Although the results of these experiments are not published, some of the findings can now be presented. The following data represent a summary of some pertinent observations:

1. Threshold determinations on chemicals are meaningless unless the purity of the chemicals is known, since contaminants have a direct effect on odor perception.

2. The use of rubber and tygon should be avoided—they should never contact a test-odorant stream.

3. Metal tubes and pipes, especially of lengths over 2 ft. should be avoided, since adsorption of the odorant on such surfaces can seriously affect odor measurements.

4. A test odor should not be injected into the nose (each nare) under any continuous pressure (flowing air stream) because:

   a. Each time a subject swallows, he can vary the pressure in his nose to apppreciably affect his reactions and sensitivity to odors.
   b. An air stream thus injected can cause cooling of the mucous membrane and in turn stimulate activity of the thermal receptors in the nose.

5. The subject should not be asked to smell any odor for long periods, especially when his test environment is not completely air conditioned and odorless[12]. A subject should be asked to sniff a test odor periodically.

6. A glass funnel presentation of the odorant is far more accurate and gives

(12) See footnote 12, page 168

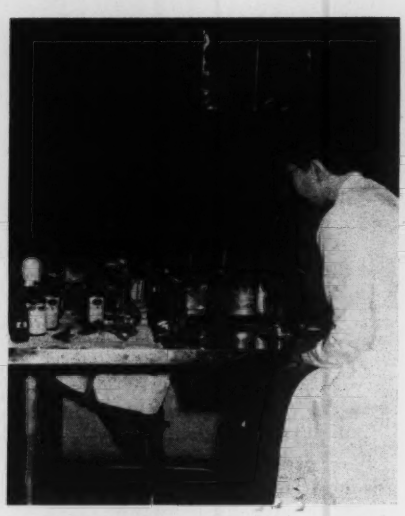

Fig. 5. The Multi-Stimulus Olfactometer. An actual experiment where a screen is used to prevent the subject from viewing the conditions of the test.

greater reproducibility of results than separate nasal stimulators. Improperly designed glass funnels, for odor presentation, will pick up mouth odors and definitely effect any experiment.

7. Each subject should be checked before any odor experiment for sniff abnormalities. The best and simplest method is to hold a glass mirror, about 4 in. x 4 in., under his nose at an angle so that an exhaled vapor pattern can be seen. Each nostril will trace a vapor condensate pattern on the mirror, and the experimenter can immediately see the dominant side of the nose or even a complete restriction of one side.

8. Any accurately determined odor-threshold concentration should never be expressed as a single weight/volume figure, but as a mean with a standard deviation. For example, bromobenzene threshold, as determined by us, was 0.0305 mg./l. with standard deviation of 0.008 mg./l., while chlorobenzene had a threshold of 0.0216 mg./l. with a standard deviation of 0.005 mg./l.

9. When determining odor thresholds on irritating chemicals, there should be provision for 2 thresholds, one denoting true odor threshold, while the other denotes a nasal irritation threshold. Otherwise, these 2 sensations can be and often are interpreted as odor threshold alone.

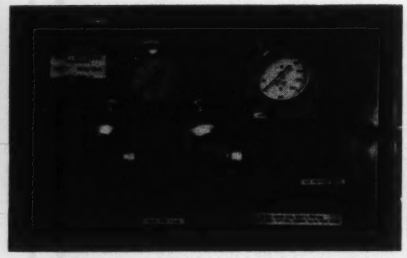

Fig. 6. Front view of the Multi-Stimulus Olfactometer

10. Well planned psycho-physical studies should be outlined for any experiment dealing with odors or their effects. The author suggests that each researcher read Guiford[23] for guidance in planning valid odor experiments.

Recent Modifications of the Mateson Olfactometer

During the last 4 years, the author has worked continuously on the problem of odor measurement and has completely redesigned the original unit shown above. Actually 2 modifications of design have been made, and the name of the unit has been changed to the Multi-Stimulus Olfactometer. This name, of course, implies that more complex odor determinations can be studied, and that a multitude of adaptations can be made to the basic unit to make it extremely versatile in types of odor research.

Fig. 4 and 5 show the Multi-Stimulus Olfactometer presently being used at Airkem, Inc., for basic threshold and product development work.

Fig. 6 and 7 show the most recent modification of the Multi-Stimulus Olfactometer.

Summary

A short review and classification of odor measurement devices has been presented to show that the odor field does not possess standard odor-measuring apparatus. An attempt has been made to show that since the olfactometers and osmometers of today vary in their working principles, and because each unit usually presents its own novel expressions of odor concentrations, correlation of reported odor thresholds are indicative of trends only. The significance of these trends can only be judged on the basis of standard deviations.

New types of odor-measurement devices, presently being developed, are described. New developments in odorimetry offer our field great possibilities, and work should be concentrated on more rapid development.

Factors affecting organaleptic odor determinations were outlined in the hope that they will aid those interested in the apparatus and techniques of this field. Likewise the presentation of new developments stimulates interest in olfactometry, and shows that strides are being made at both university and industry level.

In conclusion the author would like to say that odorimetry is not a subject for casual treatment by the engineer or chemist. Odorimetry can be made highly reliable if those working in this field are well trained and aware of the many possible errors open to haphazard or casual research. When we speak of odors, we immediately introduce the variables of chemistry, physiology, physics, and (not to be excluded) psychology. It is easy to forget the psychological aspects of odors, or even more easy to assume that they are nonexistent.

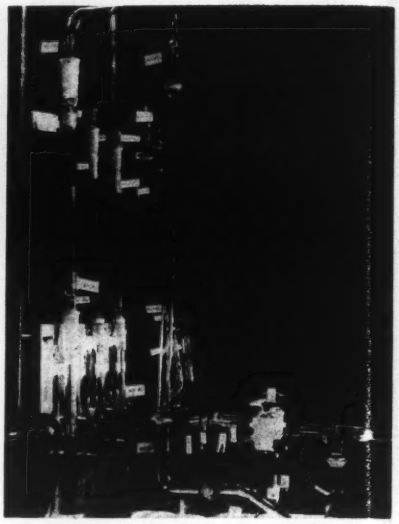

Fig. 7. Side view of the Multi-Stimulus Olfactometer

(23) Guilford, J. P., "Psychometric Methods," McGraw-Hill Book Co., Inc., N. Y., 1936.

Visual Clarity in Kiln Discharge Gases*

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Detroit, Mich.

In February 1954, the Cadillac Asphalt Paving Company requested the Western Precipitation Corporation to assist them in a program designed to eliminate dust from kiln discharge gases at their Heatherington and Ferner plant.

This paper outlines the dust-collection problem as it existed, illustrates the dust-collection process selected, describes the equipment utilized, and notes information that was obtained as a result of the operation of this system.

Since the equipment was installed in the Spring of 1954 there has been no visual dust emission from this plant despite the fact that it is one of the largest asphalt plants in the country. Two hundred and thirty tons/hr. of crushed stone, sand, etc., can be heated to 350° to 400°F., and 28,000 to 31,000 cfm. of dust-laden gas may leave the outlet end of the oil-fired kiln, but no measurable quantity of dust escapes the highly efficient dust-collecting system. During operation, essentially 100% of the dust is filtered out by passing the kiln gas through dense wool felt, 3/32 in. in thickness.

The Problem

This was not the first dust-collection system tried on this application at this plant. Wet-collection systems of various designs were tried without success. Since this plant reheats rock and sand that has previously been dried, the dust load in the gas leaving the primary collectors is quite high — in the range of 8-16 gr./ft.^{3} Centrifugal collectors and wet scrubbers, even though of efficient design, had effluent concentrations varying from 0.5 to 1.0 gr./ft.^{3}. Since 94% of the dust is smaller than 10u. that quantity of dust would offer a large surface area and produce an opaque emission.

The very fact that made this a most difficult problem for other collectors made it possible to apply a high-efficiency filter. While heating pre-dried rock and sand produced a heavy dust load, it also resulted in a low-moisture content in the gas stream that was favorable to fabric collectors.

In most asphalt plants, the kiln is used both to dry and heat the rock and sand. If the gas leaving the kiln is diluted to reduce the temperature to 180°F. to permit use of a fabric collector, the dew point of the gas leaving the kiln is still about 150°F. This is an uncomfortably low temperature differential when you consider that an asphalt mixing plant is not a continuous operation. The plant frequently starts and stops, depending on the regularity or irregularity of the arrival of trucks to carry the product to the paving-job sites.

When the kiln is used only to reheat the rock and sand, the dew point of the exit gas is about 100°F. when the gas temperature is about 180°F. This greater spread makes it possible to operate a fabric collector without fear of "mudding up" the filtering fabric, despite the frequent kiln shut-downs. Special precautions are still required for good operations, as described later, but successful operation at this plant has shown that it can be done.

Dust Collection

The dust-laden gas leaves the kiln and first passes through a primary cyclonic-type collector (Fig. 1). The gas is then tempered with cool air by means of an automatically regulated dilution damper ahead of the fan. The temperature-control point for this damper is located close to the Dualaire Reverse-Jet Dust-Collector inlet to assure gas temperatures under 180°F. at that point without excessive air dilution. A Foxboro Recorder-Controller maintains a permanent record of the temperature at this point and also regulates the air motor that positions the air-dilution damper (Fig. 2 is a typical chart from this recorder). Following the air-dilution damper is the main fan.

Excellent mixing of dilution air and hot gas is assured. Both the fan and Multiclone Collector serve as mixers with the result that there is no chance of a strata of gas entering the Dualaire at too high a temperature.

The combination of collectors from this point on may appear overly complex at first glance. However, this complexity was dictated by a need for an auxiliary system that might be used during special periods when wet materials must be fed to the kiln. During these periods the dust collecting system consists of a Multiclone and a Scrubber.

* Presented at the 48th Annual Meeting of the Air Pollution Control Association at Detroit, Michigan, May 22-26, 1955.

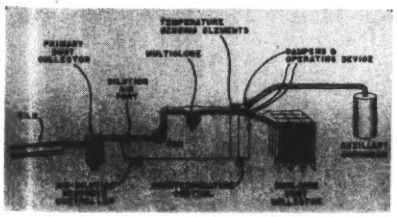

Fig. 1

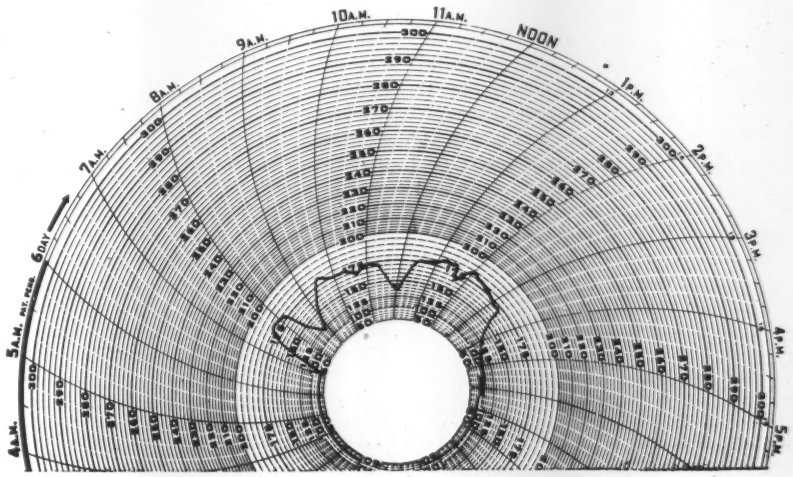

Fig. 2

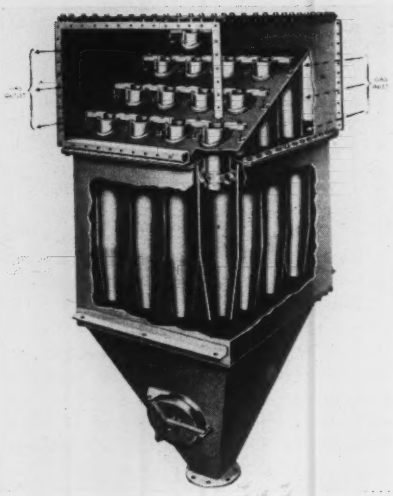

Fig. 3

During normal operations the collecting system consists of a Multiclone followed by a Dualaire Reverse-Jet Dust Collector. Both the Multiclone and Dualaire Dust Collectors are standard equipment designed and built by Western Precipitation Corporation.

The Multiclone (Fig. 3), a type 9VG10, small diameter, multiple-tube cyclone, size 70-7, serves as the secondary mechanical collector. The small diameter produces a high centrifugal force and results in almost complete collection of particles above 10 microns in size and collects a large portion of the remaining smaller particles. The unit used here consisted of seventy 9-in.-diam. cast iron tubes, arranged 10 tubes wide and 7 tubes deep in the direction of gas flow. The Multiclone reduced the dust load from about 8 to 16 gr./ft.^{3} to about 1.4 to 1.8 gr./ft.^{3}. This collector is designed for heavy duty dust-collection applications and has proven itself in service in many other asphalt plants, although its greatest use is in the collection of fly ash in coal-burning power plants.

The Dualaire Dust Collector is designated as 3 units, 3 sections, Type HR-4-W, size 4-20-19. There are 4 felt cylinders per section, each about 20-in. diam. and the effective length of each is approximately 19 ft. To suit the capacity requirement of a specific application, sections are combined to form a unit. All sections in a unit share a common drive system. If a gas-volume requirement or the space configuration dictate, several units are joined to form the installation. The installation discussed in this paper is made up of 9 sections in an arrangement consisting of 3 sections in each of 3 units. The completed installation is shown in Fig. 4.

An important novel feature of this installation was the erection procedure. Each of the 9 sections was shipped to the job site completely assembled. They were individually lifted into place on the framework, using a portable crane, (Fig. 5) and were then bolted together. No accurate record was maintained of the total man hours required, but to give some idea of the speed of erection it is interesting to note that all 9 sections were placed in position in 1½ days. Fig. 4 shows 3 sections on a flat car as they were shipped to the job site.

Between the Multiclone and Dualaire the gas passes the temperature sensing elements of the recorder-controller previously described and also an overtemperature-control device. If, for any reason, the gas temperature exceeds 180°F. at this point, the overtemperature con-

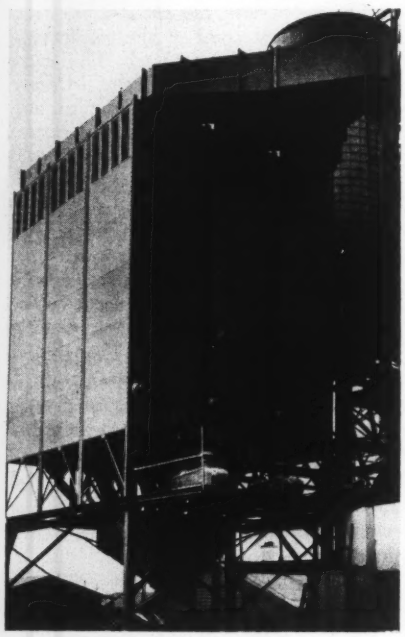

Fig. 4

troller closes the damper at the inlet to the Dualaire and opens another damper to the auxiliary scrubber. This, of course, is an emergency condition and as soon as the overtemperature condition is rectified, the dampers automatically return to the proper operating position, with the gas directed to the Dualaire. Manual control is also available to divert the gas away from the Dualaire for preheating the ducts at start-up. The auxiliary scrubber was included in the system only to take care of the special operating conditions that exist when wet material is fed to the kiln.

So-called "Dead-Man" control is used throughout the system; hence air or power failure will result in the dampers moving into a safe position and diverting the gas away from the Dualaire Dust Collector.

Operating Data

The equipment went into operation on June 23, 1954, and remained in regular operation until the scheduled winter plant shut-down in November 1954. The following data were obtained during normal plant operation:

Gas volume at inlet conditions	28,000-31,000 cfm.
Temperature	125°F.-180°F.
Filter Ratio (cfm./sq.ft.)	8.5-1 to 9.3-1
Dew point	98°
Reverse-Jet operation	40% (approx.)
Pressure drop across Multiclone	2.2 in. to 2.7 in.
Pressure drop across Dualaire	3 in. to 4 in. vertical water column
Inlet dust load to Multiclone	.8 to 16 gr./ft.^{3}
Dust load to Dualaire	1.4 to 1.8 gr./ft.^{3}
Total dust collection in Multiclone and Dualaire (average)	3030 lb./hr.

Operation of the Reverse—Jet Dust Collector

The Dualaire Dust Collector separates dust from a gas stream by filtering the gas through dense wool felt. The porosity of the fabric is maintained by means of a high-velocity jet of clean air applied to the clean side of the felt that blows the dust out of the pores and off the upstream side of the felt (Fig. 6). The dust-laden gas is introduced at the top of the cylinder that forms the filter element, and that portion that flows down to pass through the lower portions of the element aids in carrying the collected dust to the hopper.

The air jet is applied by means of ring segments around each of the felt cylinders (Fig. 7). The segments are held against the felt by factory adjusted springs that carefully control the pressure indention so critical for proper action of the reverse-jet. The self compensating

(continued on page 186)

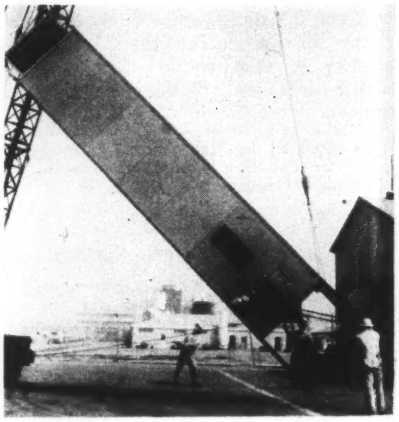

Fig. 5

Range of Applicability of Catalytic Fume Burners*

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Vapor-phase catalytic oxidation is relatively new in the field of air-pollution control, although it has long been practiced in the chemical manufacturing industry. Catalysis is involved in the production of billions of dollars worth of products each year, such as gasoline and other fuels, synthetic rubber, methanol, formaldehyde, ammonia, nitric acid, and plastics. Where a catalytic operation is used in the production of a material of value, it is usually considered a most vital part of the operation, and accordingly the plant is designed and operated in such a way to take best advantage of the nature and function of the catalyst. In air-pollution-control work, where the product of the catalyst frequently has no value, but is merely being rendered innocuous for disposal the situation is reversed. The catalyst performs a secondary function, and it becomes necessary to adapt it to the existing manufacturing operation. With the tremendous variation in the nature of materials and the circumstances of their handling prior to and during their discharge to the atmosphere, it is apparent that the application of catalysis is a problem of considerable magnitude. In the pioneering work in this field, one of our principal problems has been the determination of the specific instances of air-pollution sources which might be controlled by catalytic oxidation in a practical and economic sense. Control officials share this problem with us, and it is the purpose of this paper to delineate the limiting features of catalytic oxidation in a general way.

In several previous papers[1,2] we have outlined the operating features of the catalyst manufactured by this firm. At the risk of repetition, however, it is considered that a more detailed exposition might not be amiss, since the limits of application become much more clear in the light of consideration of the actual mechanism of catalysis.

Mechanism of Catalytic Oxidaton

The precise mechanism of heterogeneous catalytic oxidation is not well understood in spite of the fact that it has been under study for at least 150 yr. The bulk of the knowledge which has been accumulated is empirical in nature, although a good deal of progress has been made in the last 30 yr. as to the basic theoretical aspects. For example, it is now possible to develop equations for absolute reaction rates from laboratory data in some instances. The Brunauer Emmett-Teller method of determination of the surface area of catalysts is widely used in research work.[3] As intensive study of the kinetics of surface reaction begins to bear fruit, the art and experience approach gives way to science, and catalytic reactions become more predictable. This is beginning to facilitate the work of those of us who are concerned with application problems. It still must be admitted that catalysis is imperfectly understood; in fact, one authority has stated that more precise knowledge has now been accumulated on the mechanism of nuclear transformations than on ordinary chemical reactions carried out by catalysis.

Broadly, catalytic oxidation proceeds through 3 steps:

1. Adsorption on the active surface
2. Chemical reaction
3. Description

A consideration of the nature of these steps will well serve our present purposes.

Adsorption

All solid surfaces tend to adsorb extraneous substances to some extent, usually gases or vapors. This arises from the fact that surfaces are naturally imbued with a content of energy which they tend to lose, the energy consisting of an intensity factor (surface tension) and a capacity factor (surface area) just as mechanical energy consists of force and distance factors. A system can lose energy either by contracting the surface (this happens when water falls through the air and assumes spherical shape) or by decreasing its surface tension. The rigidity of a solid surface prevents such contraction. A freshly prepared solid surface will invariably attract to itself a film of gas molecules which cover the surface as a more or less continuous film, thus reducing the abrupt discontinuity between the solid and the surrounding gas, and reducing the surface tension and the energy content. Equilibrium is soon reached, and further adsorption or desorption awaits change in the ambient conditions.

All active catalysts have this property of adsorption to a marked degree. In addition, they are distinguished from other surfaces in that the process does not stop at that point in the presence of certain reactive substances. Strong adsorption of reactive substances on the active surface results in close juxtaposition as well as possible loosening of chemical bonds. In addition, heat of adsorption is released as the gas molecules enter into the surface film, which is comparable to the liquid state, the heat being comparable to heat of condensation. A chemical reaction occurs, which would not occur at appreciable rates in the absence of the catalytic surface under the same conditions. This is accompanied by a release of energy and desorption of the products of the reaction. Unlike a simple adsorption, in the case of a catalytically active surface this process may be carried out continuously.

Further consideration of the adsorption process is of value in the practical application of catalysts. Fig. 1 illustrates the profile of a gas stream passing between 2 catalytically active surfaces, which are shown in the form of planes

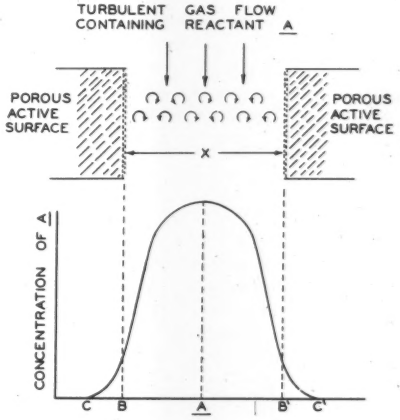

Fig. 1. Diffusion of Reactant Molecules to Catalyst Surface

(1) Ruff, R. J., *Industrial Heating* (March, 1950).
(2) Ruff, R. J., *The Plant* (June, 1950).
* Presented at the 48th Annual Meeting of the Air Pollution Control Association at Detroit, Michigan, May 22-26, 1955.

(3) Braunauer, S., Emmett, P. N., and Teller, E., *J. Am. Chem. Soc.*, **60**, 309 (1938).

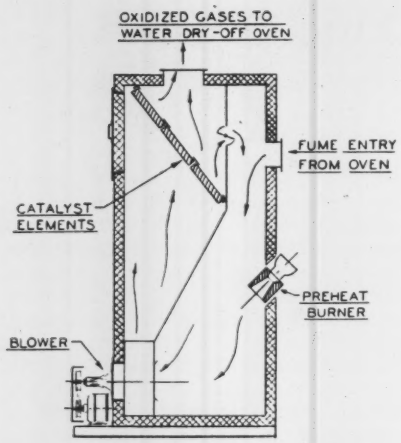

Fig. 2. Type R-C Heat Recovery System

for simplicity.[4] Consider a single molecule of reactant **A** as it passes through this zone in random motion, in addition to its travel in the direction indicated. It must diffuse to close proximity to the catalyst surface in order to be adsorbed. The velocity of its random motion is directly proportional to the absolute temperature, and inversely proportional to the square root of its molecular weight. Its chance of striking the active surface will vary inversely as the square of the distance X. The lower portion of the sketch represents a profile of the concentration of **A** across this zone. As the molecules of **A** diffuse into the porous surface, at some point they are adsorbed, reacted and desorbed. Thus, the concentration of **A** falls to zero at some point below the gross surface of the catalyst—designated *C* and *C'*. At the gross surface, points *B* and *B'*, the concentration is much lower than at point *A*. For oxidation reactions which are very fast, and for catlysts of high activity, it is considered very likely that the diffusion to the active surface is the slowest of the several steps occurring, and is one of major importance in catalyst design and operation.

Several points are apparent. First, it is clear that turbulence will assist in the diffusion process and it follows that shapes of catalyst supports promoting laminar flow should be avoided. Secondly, the clearance between active surfaces should be small. It is evident that a given catalyst might be expected to have a higher capacity for reacting molecules of low molecular weight than for heavy molecules, due to the higher diffusion rates of the former. Also, it is clear that entrained particles, even if they are flammable, would tend to pass through the zone without being adsorbed, since they have essentially no random motion, due to their large mass compared to a gas molecule. They merely follow the air stream, and in a catalyst bed contact with the active surface would be by impingement only. In the case of sub micron sizes, the aerosol particles may not have enough mass to cus across the air stream as it rounds bends, and therefore might pass through the entire catalyst bed, as they do through filters. Of course, in the event that the catalyst is operating at a high temperature, the particle may be vaporized before leaving the bed.

(4) Wheeler, Alhorn, "Catalysis", Edited by P. H. Emmett, Vol. 2, p. 132, Reinhold, 1955.

Chemical Reaction

Turning now to the chemical reaction occuring on the active surface, in the case of oxidation reactions it is probably necessary for molecules of both the combustible substance and oxygen to be adsorbed on adjacent sites. As mentioned previously, chemical bonds are probably loosened, facilitating the reaction or in effect partially overcoming the energy of activation. For the same reaction in the gas phase, the distribution of energy among the molecules of one of the reacting substances would follow the normal statistical distribution curve. At the high end, a few of the molecules may be sufficiently energized to react at a given temperature. Unless the heat of reaction is sufficient to energize an equal number of molecules to the same degree or more, the reaction does not proceed. As the temperature is increased, a point is reached where the chain reaction proceeds, provided that the concentration of the substance is above the lower flammable limit. In the presence of a suitable catalyst, however, combustion is not restricted to concentrations above this limit, due to the adsorption effect which largely removes the activation-energy barrier. To illustrate, air streams containing hydrocarbons at concentrations below the flammable range must be heated to 1200°F or more to initiate and maintain oxidation, while the same streams are readily oxidized over a precious metal catalyst in the range of 475-600° F.

Desorption

The third step in the catalytic oxidation process consists of desorption of the products of combustion. When the oxidation is complete, the products are of relatively low molecular weight, and are desorbed readily. High temperatures on the catalyst surface, which result from relatively high concentrations of flammable material in the stream, favor rapid desorption.

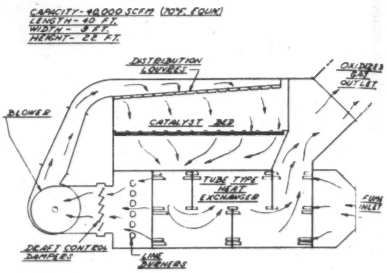

Fig. 3. Type S-R Fume Incinerator

A perennial problem in catalytic operations is the determination of the rate-limiting step. Once this is known, the chemical and physical form of the catalyst may be altered to minimize the bottleneck, and operating conditions may be selected toward the same end. This is extremely difficult to determine by direct experimental approach as there is, obviously, no one answer for all catalytic operations. The limiting rate might easily lie in the chemical reaction itself, considering the fact that only a small portion of the total surface is actually active. On some catalysts, this has been determined by means of total surface area measurements by the B.E.T. method, together with controlled poisoning experiments. In this latter case, materials were added in carefully controlled amounts, the "poisoning" consisting of more or less permanent blocking of the active sites by substances which are not desorbed. On some catalysts, the active surface has been shown to be in the order of 4% of the total surface. In such case, improvement would lie in the direction of increasing the total surface area and the content of active centers, if possible. These probably consist of imperfections in the crystal lattice of the active material, or possibly in fragmentary projections where the attractive forces are least satisfied. In the case of catalytic molecular re-arrangements or partial oxidations, desorption might well be the rate-limiting step. In such cases, a balance must be struck between temperatures high enough to favor desorption and those too high to permit formation of the desired reaction products.

In the case of complete oxidations (as are desirable for purposes of air pollution control) the preponderance of evidence indicates that the rate-limiting step lies in the adsorption process. Properly prepared precious metal catalysts are highly active, and the desired reactions are inherently rapid. Also, these conditions favor rapid desorption. The ideal catalyst for this purpose would therefore be designed in such a manner as to promote turbulence in the stream, would

have close spacing between the active surfaces, and would consist of thin members so that the fraction of the total space occupied by the catalyst supports would be at a minimum.

General Principles of Applicability

From the foregoing, it is apparent that the general field of applicability for vapor-phase oxidation in the air-pollution-control field lies in streams containing combustible matter at concentrations below the lower limit of explosibility. The limitations may be physical or chemical, or practical and economic.

The only limitation of a strictly physical nature is that the combustible substance must be in the vapor phase or must be vaporizable at a reasonable temperature. As previously mentioned, this is necessary in order that adsorption may take place. In practice, many successful installations have been made where the material to be oxidized is extremely difficult to vaporize, being present in the stream as aerosols or entrained droplets. Examples include effluents from asphalt blowing operations, varnish and resin kettles, and phthalic anhydride plants. In these cases, preheating is provided in part by means of heat exchangers, or by recycling hot oxidized gas. Hold-up time in the hot zone is kept as long as possible, thus vaporizing as much of the material as practical. When there is sufficient actual vapor present with the droplets, or when some light fractions are produced by partial thermal cracking during preheating, catalytic oxidation is initiated by this portion and the remaining aerosol thereafter is vaporized and adsorbed as it passes through the catalyst, this being the hottest zone.

It is obvious that noncombustible inorganic solids are not affected by the catalyst, and should be absent from the stream lest they accumulate and cover the active surface. Perfectly clean streams are rare in industrial applications, and again, as in a practical matter, reasonable amounts of unburnable solids do not always rule out the use of catalysts. Successful operation has been achieved under condition of high loads of unburnable solids by the use of expanded catalytic elements, which minimize their tendency to act as filters. With reasonably frequent cleaning, performance is satisfactory.

As to chemical limitations, the first and most obvious requirement is that the material to be oxidized must yield innocuous products in order to serve the purposes of air-pollution control. This, of course, is true in the case of compounds of carbon, hydrogen, and oxygen, which, indeed, cover a wide field. In the case of hydrogen sulfide, or organic compounds containing sulphur, catalytic combustion, regulated so as to operate at temperatures below 675° F. or above 1250° F., will result in the conversion of the sulphur to sulphur dioxide, which is certainly less offensive and less dangerous than many of the original substances. No general rule can be stated for organic compounds containing nitrogen; the effluent may contain free nitrogen or its oxides, depending on the conditions of operation. It is obvious that the products of combustion must be entirely volatile, so that the desorption step may be accomplished. This rules out organo-metallic compounds as a class, esters of phosphoric acids, and silicones, all of which yield solid oxides which quickly coat the active surface.

A final chemical limitation is that specific catalyst poisons must be absent. As a class, these are vapors of pure metals, such as mercury, arsenic, zinc, lead, etc. As mentioned previously, these quickly stop catalytic action by permanently occupying the active sites. The occurrence of intolerably high concentrations of these substances is relatively rare in air-pollution-control problems.

Practical and economic limitations are always with us. Precious metal catalysts are expensive, and must be used in proportion to the total volume of air or other gas to be handled, taking the other factors which affect the size of an installation duly into account. It follows that an offensive stream should be reasonably well isolated, its volume being restricted at the source as far as possible in order that the size and cost of a catalytic unit may be kept within bounds. In general, the higher the concentration of the combustible substance in the stream, the more economical the unit becomes. Where concentrations are in the order of 10 Btu/ft.^{3} or more, it frequently become practicable to recycle part of the effluent from the catalyst for preheating, and in many cases the system may become self-sustaining. A unit of this type is illustrated in Fig. 2. In other cases, the hot effluent may be used for heating make-up air to factory work spaces, operating dry-off ovens, or it may be returned to the work cycle in industrial ovens. Where the concentration is low, and is not subject to change, the preheating load may be considerably reduced by the use of heat exchangers utilizing the hot exhaust gas. Such a recuperative system is illustrated in Fig. 3.

TABLE I

Minimum Temperatures of Initiation of Catalytic Oxidation of Hydrocarbons

Saturated Aliphatics	Temp. deg. F.
Methane	760
Ethane	680
Propane	650
n-Butane	570
n-Pentane	590
n-Hexane	630
n-Heptane	580
n-Octane	490
n-Decane	500
n-Dodecane	540
n-Tetradecane	550
Aromatics	**deg. F.**
Benzene	440
Toluene	460
O-Xylene	470

Catalyst Performance

A thorough treatment of the performance of the catalyst developed by our firm is beyond the scope of this paper, but some general principles may be stated and illustrated. One of the prime factors which must be considered in the design of catalytic oxidation units is the capacity of the catalyst for complete oxidation in terms of total air and combustible matter. This is greatly affected by the prevailing conditions, including the nature of the matter to be oxidized, its concentration, and the operating temperatures. These effects are so pronounced as to require a competent and experienced designer. Accordingly, catalytic oxidation units are not bought off-the-shelf, but are specially designed for various applications. A certain degree of standardization, however, has been accomplished.

Another factor which must be taken into account is the minimum temperature at which catalytic oxidation can be initiated. The variation in these temperatures for 2 homologous series of hydrocarbons is shown in Table I. These measurements were taken at an average capacity loading used in commercial units for one of our standard catalyst forms, and at a hydrocarbon concentration corresponding to approximately 10% of the lower limit of flammability. It will be noted that the lightest member of the series of saturated catalytic hydrocarbons requires the highest temperature to start oxidation, and that this temperature declines as the chain length is increased to 8 carbon atoms, whereafter it increases as the molecule becomes larger. In the short series of aromatics, the minimum temperature increases with molecular weight, and this entire series fires at lower temperatures than the aliphatics. In all cases, these values would vary considerably with the volume loading and the concentration of hydrocar-

(continued on page 184)

Recommended Standard Method for Continuing Dustfall Survey (APM l-a)*

Introduction

The suggested standard method of dustfall collection, as set forth in the following sections, is presented in an effort to promote a uniform approach to measurement of rate of dustfall.

The measurement of rate of dustfall as presently practiced is subject to various possible errors in the technique of measurement and in the interpretation of the final result. Dustfall is influenced by rate of emission, wind speed, wind direction, precipitation, thermal air currents, eddies produced by the terrain or construction in the vicinity, and undoubtedly other influences; and measurement of the rate of fall becomes a problem in proper sampling. It is essential in a sampling technique that new errors are not introduced by a variety of test methods. The complications of the naturally occurring influences are sufficiently complex without adding to them unknown factors produced by collecting devices of different design. While it is necessary to have a good method of collection, economic costs and lack of time for experiment also influenced the committee in its selection of one method as being most practicable from a number of good methods. The important thing in collecting data which will be compared among a number of observers in a number of regions is that the method of collection be standardized so that valid comparison is possible.

The suggested standard method applies only to the measurement of average rate of dustfall over a large area; it has no application to locating specific sources of pollution, which is a complete problem of itself to be considered separately by this committee at a later date. The suggested standard method is presented as the best procedure, in the opinion of the committee, after considerable discussion and review of questionnaires submitted by 30 active groups.

Section A
Design of Collector

1. *Shape and Size*†
   a. Open-top cylinder with vertical sides
   b. Diameter—5 in. plus or minus 1 in.
   c. Height (depth)—2 to 3 diameters
2. *Material of Container*‡
   a. Glass
   b. Stainless steel

Section B
General

The following standard practices are for conducting a continuing dustfall survey for an entire area as distinguished from a dustfall survey for part of a special investigation of a particular situation. Many of the principles which apply to the continuing dustfall survey may also be used in the special investigation procedure. It is believed that the difference between the two procedures will be the avoidance of undue local sources of pollution in the continuing dustfall survey, whereas such is not the case in the special investigation of a particular situation. In the special investigation procedure, the selection of the sampling sites will center around the suspected source of undue local pollution.

Editor's Note: This is the first publication of a report from the Technical Coordinating Committee. This is a *tentative report* at this time and does not commit the Association to underwriting the report or giving to it any authoritative connotation.

Referring to the By-Laws of the Association, in Article XV we find the procedure for handling technical coordinating committee reports as follows:

Section 4. Upon completion of the task of any subcommittee, its recommendations shall be submitteed to the Technical Coordinating Committee for study and coordination . . . and, if approved by this committee and the Board, the report shall be published in the next issue of the *Journal* for consideration of the membership. Constructive criticism of the report shall be invited and given to the subcommittee for its consideration. If advisable, the subcommittee shall re-submit its amended report to the parent committee . . .

This report was submitted to the Technical Coordinating Committee in July, 1954, and comments, corrections and additions, deletions, etc., were added to the report. It was then submitted on August 22, 1955, to the Board of Directors who have authorized publication in the *Journal* as a tentative report.

Kindly direct your comments or criticism to the office of the executive secretary before November 1, 1956, for consideration by the Air Pollution Measurements Committee.

Classification of the Area

The area served by each jar will be classified according to the character of urban activity in the vicinity of the station. The type of activity within one-quarter mile of the station will determine the primary classification. A secondary classification will be determined by the type of activity within one-half mile from the station. Classification shall always be reported by primary and secondary classification, such as Zone AA or AF. Note should be made of any major source or sources of heavy dust discharge within one mile of the station.

A dwelling unit will be defined as a building or part of a building occupied by one family.

The areas will be classified as follows:

Zone A—Residential, low density (less than 10 dwelling units per acre and non-rural)

Zone B—Residential, high density (more than 10 dwelling units per acre)

Zone C—Commercial, neighborhood shopping district

Zone D—Commercial, central business district

Zone E—Industrial, with low air-pollution potential

Zone F—Industrial, with air-pollution potential

Zone G—Rural, 1 dwelling unit per 5 acres or larger area

Selection of the Site for the Sampling Station

A sampling station must have a free exposure so that the sampling jar collects the sample by gravity settling only. It must be free of undue local sources of pollution and free of interference from buildings or other higher objects or structures. Accessibility and security (freedom from tampering) are major considerations in the selection of the site.

In addition to the foregoing general rules, the following specific recommendations will be used as a guide in the selection of a good site. When local conditions will not allow recommendations to be met, note should be made.

1. The top of the dustfall container shall be a minimum of 8 ft. and a maximum of 50 ft. above the ground, or 4 ft. minimum above any other surface such as a roof. Higher objects such as parapets, signs, penthouses and the like, must not be more than 30° from the horizontal, as measured in (4) below.
2. Public buildings such as schools, fire stations, libraries, etc., are most favor-

† The above design is an arbitrarily selected interim specification because of the lack of sufficient aerodynamic data. It is intended that retention with different liquid levels in different shapes of containers shall be studied in order to develop a collector that can be better justified.

* Prepared by the Committee on Air Pollution Measurements of the Air Pollution Control Association.

‡ Other materials of construction should be investigated.

able to public agencies because of their accessibility and security.

3. Care should be taken to avoid undue influence from one chimney, e.g., the chimney on the building of the sampling station. Whenever possible, set the sampling jar more than 10 stack lengths from an operating stack and up wind (prevailing).
4. When higher buildings in the immediate vicinity cannot be avoided, the top of any building should not be more than 30° above a sampling point. That is, a line drawn from the sampling jar to the nearest edge of the highest point on any building should form not more than a 30° angle with the horizontal.

Spacing Between Stations

See Section D.

Control Station

For a continuing survey, a control station is recommended. A control station will be located in a Class G (rural) area sufficiently removed from local influences so that it will measure the natural dustfall characteristic of the geographical area under study. *It is of the utmost importance that the control station be free of local or regional influence. However, if a number of good sites are available, it is an advantage to locate the control station upwind (prevailing wind) of the area under study.*

Maintenance of the Site

Once selected, a site should be maintained unless conditions occur to cause undue influence on the sample or to create an unsatisfactory condition.

Length of Sampling Period

A sampling period should be one calendar month, corrected to 30 days. Allowance of plus or minus 2 days is permitted in setting out and/or collecting the sampling jars.

Section C
Collection and Analysis

The following procedure is recommended for the collection and analysis of dustfall samples:

1. Dustfall containers shall contain distilled water when first exposed, and water shall be maintained in the container at all times. Frequent inspections shall be made to insure that the container does not go dry or overflow in periods of rain.
2. Quaternary ammonium chloride shall be used as an algae inhibitor. 1 to 2 ppm. by weight (1 to 2 mg./l) based on the weight of water in a filled container shall be added to each container at the start of each month.
3. Freezing should be avoided, even when using nonbreakable containers, as liquid is necessary to prevent loss of settled material by wind action. Isopropyl alcohol will serve as antifreeze without hindrance to the analysis.
4. All transfers shall be made in the laboratory. A sufficient number of clean containers may be carried to the sampling stations, exchanged with the exposed containers, and the exposed containers returned to the laboratory for transfer and subsequent analysis. Containers shall be properly covered during transfer to avoid possibility of extraneous material pickup during transit.
5. Extraneous material shall be removed by means of a chemically inert 20 mesh screen. An abundance of small insects may require the use of a screen smaller than 20 mesh. In this case, the oversize material shall be examined to avoid removing material which is properly a portion of the sample.
6. The error in analytical results introduced by bird droppings may be slight or considerable. Where bird droppings have become a problem, the only protection is the use of a bird ring about the container to provide a perch at a distance.
7. The analyses to be made on the dustfall samples shall be based upon the main objective of the measurement. An attempt should be made to obtain such information from the samples as is consistent with local conditions. This information generally includes total and water-soluble solids, a suggested procedure for which follows. In some instances special information may be needed, such as the pH of the collecting liquid, total combustible, metals, organic and inorganic radicals, etc.
8. Blanks shall be run with all determinations in order that a correction can be made for any impurities which may be present in the collecting and transferring liquids or reagents.

Determination of Water Soluble and Total Solids

No Antifreeze Present

Free the sample from extraneous materials by passing it through a 20-mesh screen into a Pyrex beaker of suitable size. If necessary, adjust the sample volume to a minimum of 300 ml. with distilled water, heat to boiling, and filter through a weighed, 35 ml. Alundum filtering crucible (medium porosity RA 360). Free any material adhering to the walls of the sample container with a rubber policeman and wash this material into the crucible with distilled water. Dry the crucible in an oven at 105°C. for approximately 3 hr. Cool in a desiccator and weigh. Continue the drying procedure until crucible reaches constant weight. The increase in weight of the crucible represents the total water-insoluble material in the deposit.

In a Pyrex beaker of suitable size, evaporate the filtrate down to a small volume. Transfer the solution to a weighed Pyrex beaker or evaporating dish (approximately 100 ml. capacity). If fluorides or caustic materials are suspected to be present, it may be desirable to use platinum ware for the final evaporation step. Continue evaporating on the hot plate to a volume of approximately 25 ml., then transfer the evaporating vessel to a steam bath or to a 105°C. oven. Evaporate to dryness. Heat the dry material for approximately 2 hr. in an oven at 105°C. Cool in a desiccator and weigh. Continue the drying procedure to constant weight. The increase in weight of the evaporating vessel represents the total water-soluble material in the deposit. The sum of the water solubles and insolubles is, of course, the total solids.

Antifreeze Present

If antifreeze (a volatile type) is present in the sample, proceed as follows:

Free the sample from extraneous materials by passing it through a 20-mesh screen into a Pyrex beaker of suitable size. Evaporate to a small volume on the hot plate, then continue the evaporation to dryness on a steam bath or in an oven at 105°C. When dry, add about 300 ml. of distilled water. Clean the walls of the beaker with a rubber policeman, making certain that all of this material is in the water suspension. Heat to boiling and filter through a weighed Alundum crucible. Again the material adhering to the walls of the beaker should be policed and washed into the crucible with distilled water. From this point on the procedure is the same as that when no antifreeze is present.

Section D
Reporting of Data

The initial plan for conducting a dustfall survey will govern the usefulness of the data reported. Measuring rate of dustfall over a broad area is typical of drawing samples from any statistical population. It is advisable to simplify the problem whenever possible; and in sampling a large area, such as a city, simplification is possible by dividing the area into standard zones as defined in Section B. These zones can then be compared with each other or with other zones of the same class. Each zone will be considered a separate population for sampling purposes.

It is recognized that any sampling procedure is best carried out by the collection of random samples. However, due to the limited number of suitable sampling sites available in an urban area of any size, and the permanent nature of the station, the selection of sites by purely random means will be impractical.

A minimum of 4 sampling stations shall be selected for any classified zone or group of similar zones within a geographical location that it is desired to study. Section B defines the classification of zones from A to G, but all zones need not be used for each problem. The number of sites used and the number of zones involved will vary with each geographical area. The 4 stations should be located at sites which represent as nearly as possible the fall of dust within the zone without duplicating each other. The plan of spacing, therefore, should be as much as possible an orderly arrangement having equal distances between neighboring sites, or between neighboring sites and the boundary, while spread throughout the zone.

A chart has been prepared (Table I) which can be used for summarizing data for an entire year. A space has been provided for a mean and its limit as discussed in Section E. The summary refers to dustfall by total weight, and does not consider the insoluble and water soluble fractions, etc., which may be reported separately.

Weather data should be included in summary form as an aid to comparison. For this reason, the weather data itemized should be considered only the minimum required, and should be amplified whenever possible. The itemized data is available from United States Weather Bureau summaries, but if precise local weather information is available, such as average wind velocity by direction, and duration of wind by direction, it should be included. *Miscellaneous air-pollution information, such as total solid-fuel consumption or any information relating to the deposition of airborne solids, should be included when available.*

The unit of rate of dustfall used in the suggested standard method is pounds per thousand square feet per thirty days (lb./1000 ft.^{2}/30 days). This unit, *representing the weight of material falling on an area roughly the size of an average dwelling,* it is felt, can instill a better appreciation for the conditions of dustfall than the old unit of tons per square mile per month.

Section E
Interpretation

It is essential that sampling be not only conducted but also interpreted on a statistical basis. Although the many variables involved make interpretation difficult and often inconclusive, comparison of the means only makes no allowance for the natural fluctuations involved, and drastic misinterpretations can result. The suggested standard method recognizes the statistical nature of dustfall measurement, even though the treatment has not beyond criticism. It is hoped that further refinement can be introduced as been over-simplified and consequently is more information is gained concerning the exact nature of this problem and as the principles become accepted.

Proper interpretation of the results of a dustfall survey is dependent on the understanding of the measure itself. The intent of this measure is to describe the mass rate of fall of particulate matter under the conditions of each test. It measures the quantity of material which will settle on horizontal surfaces, and consequently is useful in describing one phase of community dirt—that material which must be swept from porches, steps, automobiles or other unsheltered locations. This type of test will not measure the total dust content of the air, and therefore cannot describe the general dirt level of a community, and it cannot be used to measure the rate of emission from sources, since it is subject to the "conditions of each test." These conditions will vary from place to place and from time to time at one place, and the rate of dustfall will change accordingly. Consequently, one community may show a high rate of dustfall and another community may show a low rate of dustfall even though both are producing identical contaminants, and at the same rate of emission. Furthermore, the rate of dustfall, while an important figure, does not in itself fully describe the effect of dustfall on community life, since the physical and chemical nature of the dust must be considered as well.

Usually the dustfall survey is conducted to observe any changes which can be attributed to man-made conditions. Dustfall is influenced by so many meteorological factors that extended periods of sampling are necessary to show significant trends. Comparison of dustfall data (properly collected) between cities is possible, but the reason for the differences may not be apparent unless the influencing factors are studied in detail. Weather data should be examined within the period for comparison, and some idea of the quantity of rainfall, most frequent wind directions, average speed of wind, etc., should be had for both periods. Considerable judgment is required in deciding when weather conditions are comparable and when they are too divergent. Like many other situations, no precise rule can be applied and the personal judgment of the observer becomes a measure of the usefulness of the result. However, an awareness of the serious influence of these factors is of itself a major benefit.

The custom in reporting results has been to tabulate data and compute the mean (or average) value for each samp-

TABLE I Rate of Dustfall Summary-

Month	Dust Fall by Zone																			
	Site. No.						Mean	Limit ±	Site No.						Mean	Limit ±	Site No.						Mean
	1	2	3	4	5	6			7	8	9	10	11	12			13	14	15	16	17	18	
Jan.	3.7	4.4	—	—	—		3.5	0.8															
Feb.	2.5	—	—	—	—		4.1	0.6															
Mar.		—	—																				
Apr.		—	—																				
May		—	—																				
Jne.		—	—																				
Jly.		—	—																				
Aug.		—	—																				
Sep.		—	—																				
Oct.		—	—																				
Nov.		—	—																				
Dec.		—	—																				
Mean	2.4	1.9	3.6																				
Limit ±	0.8	0.5	1.1																				
Zone	Mean 3.7±0.4								Mean 3.3±0.22								Mean 2.4±0.47						

Total Population.....

ling station or some other convenient design. A final figure is often obtained which is the grand mean of all tests for a definite period and which purports to give the mean rate of fall for the test area. A mean so obtained is a neat summary of conditions which is a useful yardstick for comparison. It is recognized that the evaluation of the mean value alone will serve in many situations. However, the use of the mean alone may result in erroneous conclusions in many other situations which cannot be appreciated without limits derived by statistical methods. It is recommended that a reported mean be accompanied by its limits, as shown in the table discussed in Section D. A full discussion on the use and computation of limits is included in the Appendix.

Section F

Recommendations for Future Work

The preparation of the present standard method for a general survey of rate of dustfall over a broad area disclosed several avenues which require further exploration for improvement in procedure. The design of the container should be explored so that the most satisfactory container from both a collection and a cost standpoint can be recommended. The design as it affects dust retention should also be investigated. Water is essential at present so that dust can be retained in the jar. However, the antifreeze required by the water in cold weather makes the analysis awkward or servicing burdensome, depending on the antifreeze used. The use of baffles which might retain dust in the absence of water is one approach that should be investigated. Lastly, the committee should direct its efforts to a procedure for using rate of dustfall to locate the source of the dust in question. It is hoped that the design problems can be submitted to a proper organization qualified to conduct such an investigation.

Appendix

Computations — Use of Limits

The suggested standard method produces for each zone a mean and its limits for each sampling period, and both figures are recommended wherever a mean is reported. Since the variability of influencing factors described above will affect the value of the mean even under ideal conditions, the limits will indicate the reliability of that figure. Furthermore, the laws of sampling show that in groups of samples all collected under conditions deemed equally acceptable, a variety of answers will result. Therefore, a change in sampling mean of itself is not significant. A change in sampling mean must exceed the normal change to be expected before it is indicative of a new situation.

Before relative dirtiness of two or more zones can be assessed, some idea must be had of the reliability of the means of the samples taken in the zones. The limits calculated will provide that help to judgment. Continuing trends must also be judged in the same manner, and limits plotted on a graph will help in judging the reality of trends shown. The following examples will help to clarify the use of the above procedures.

Reliability of a Mean

The reliability of the mean of a group of N samples is shown by the limits computed from the standard error of the mean in the following manner:

N = number of samples in the group
δ = standard deviation for that group
M = mean of the group of N samples
δ_m = standard error of the mean
X = value of each sample

$$\delta = \sqrt{\frac{\Sigma X^2}{N} - M^2}$$

$$\delta_m = \frac{\delta}{\sqrt{N-1}}$$

$$\text{Limit} = K\delta_m$$

Assume the rate of dustfall has been measured each month at one location for one year. What is the average (or mean) rate of dustfall at that location?

$N = 12$
X = Values given below in lb/1000 ft.²/30 days

	X	X^2
January	3.5	12.25
February	2.2	4.84
March	3.1	9.60
April	2.4	5.75
May	1.9	3.61
June	1.3	1.69
July	1.5	2.25
August	2.0	4.00
September	2.3	5.29
October	3.2	10.24
November	3.0	9.00
December	2.2	4.84
12 |	28.6	73.36
	2.38	

$M = 2.38$
$M^2 = 5.66$
$\Sigma X^2 = 73.36$

$$\delta = \sqrt{\frac{73.36}{12} - 5.66} = 0.67$$

$$\delta_m = \frac{\delta}{\sqrt{N-1}} \quad \frac{0.67}{\sqrt{11}} \quad \frac{0.67}{3.32} = 0.202$$

otal Weight Only. Chart for Year.....

				Weather Information						
				Wind		Avg. Temp.	Total Precip.	No. Storms	No. Fogs	Total Hrs.
imit ±	Site No. 19 20 21 22 23 24	Mean	Limit ±	Prev. Dir.	Avg. Vel.					Sunshine
	Mean 1.7±0.39									

otal Area.....(Sq. Mi.)

TABLE II
K Values for Limits

No. of Samples	13	4.3	3.2	2.8	2.6	2.5	2.3	2.4	2.3
Value of K	2	3	4	5	6	7	10	8	
No. of Samples	11	12	13	14	15	16	18	17	19
Value of K	2.2	2.2	2.2	2.2	2.2	2.1	2.1	2.2	2.1
No. of Samples	20	21	22	23	24	25	all values higher		
Value of K	2.1	2.1	2.1	2.1	2.1		2.0		

Throughout the standard method a confidence level of 5% has been used, and the limits are established accordingly. Consequently, a result written at 3.0 ± 0.5 lb./1000 ft.²/30 days means that there are 95 chances in 100 that the true mean value lies somewhere between 2.5 and 3.5. The limits will vary with the number of samples in the group and the standard error of the mean as follows:

$$\text{Limit} = K\delta_m$$

The value of K is obtained from Table II

Where $N = 12$, K is found to be 2.2
Therefore, limit $= (2.2)\ (0.202)$
$= 0.444$

This is rounded to 0.44. Consequently, the mean is not necessarily 2.4, but may lie anywhere between 1.96 and 2.84, and will be expressed as follows:

$M = 2.4 \pm 0.44$ lb./1000 ft.²/30 days

The same procedure can be used to obtain the limits for the mean of all samples collected in one month as is the common practice. The annual summary, showing the graph of the mean for each month, can report probable trends more dependably if the limits are also plotted. Fig. 1 shows the use of limits in judging the reality of the trends shown.

Significance of a Difference

Since the mean determined by a group of samples is only true within limits, comparison of 2 means to find the improvement or worsening of conditions must be calculated as shown below to learn if the difference of means is real or is only the result of normal variation in sampling. The computed t (significance ratio) is compared to a value to be found in Table III. If the computed t is less than the table value, no difference in means is established, but if the computed t is equal to or greater than the table value, a difference in the means is considered to exist.

In calculating the value of t, it is important that the 2 groups to be compared are the same size or nearly so. If N_1 and N_2 differ considerably, the means from those groups should not be compared by this test:

Let

N_1 = number of samples in group for 1951
N_2 = number of samples in group for 1952
δ_1 = standard deviation for group in 1951
δ_2 = standard deviation for group in 1952
M_1 = mean of group for N_1 samples 1951
M_2 = mean of group for N_2 samples 1952
X_1 = value of each sample 1951
X_2 = value of each sample 1952
t_2 = significance ratio (by which the possibility of a difference between 2 groups is accepted or denied)

Then

$$\delta = \sqrt{\frac{\Sigma X^2}{N} - M^2}$$

$$t = \frac{M_2 - M_1}{\sqrt{\left(\frac{N_1\delta_1^2 + N_2\delta_2^2}{N_1 + N_2 - 2}\right)\left(\frac{N_1 + N_2}{N_1 N_2}\right)}}$$

Illustrative Case

Assume the rate of dustfall in the previous example was determined for 1952, and it is desired to compare it with samples collected at the same location during 1951 to determine whether any change has occurred.

$N_1 = 12$ samples collected 1951
$N_2 = 12$ samples collected 1952
X_1 = values given below in lb./1000 ft.²/30 days for 1951:

	X_1	X^2_1
January	2.1	4.41
February	3.3	10.89
March	3.7	13.69
April	2.4	5.76
May	2.2	4.84
June	1.0	1.00
July	1.4	1.96
August	1.5	2.25
September	1.5	2.25
October	1.5	2.25
November	2.4	5.76
December	2.1	4.41
12	25.1	59.47
	2.09	

$M_1 = 2.09$
$M_1^2 = 4.37$
$\Sigma X_1^2 = 59.47$

$$\delta_1 = \sqrt{\frac{59.47}{12} - 4.37} = 0.77$$

X_2 = same as previous problem
$M_2 = 2.4$ (See previous problem)
$\delta_2 = 0.67$ (See previous problem)

$$t = \frac{2.4 - 2.1}{\sqrt{\left(\frac{12\ (0.77)^2 + 12\ (0.67)^2}{12 + 12 - 2}\right)\left(\frac{12 + 12}{(12)\ (12)}\right)}} = 0.97$$

Referring to the table of t values, when the total number of samples considered is 24, t is found to be 2.1.

Since t computed is less than t from the table, it can be said that there is no significant difference between the 2 means. As applied to the problem, the meaning is that there was no true difference in the rate of dustfall in 1951 and 1952 at that location, and the fact that the mean for 1951 is 2.1 and the mean for 1952 is 2.4 represents only normal sampling error.

19.....
Summary for City of.....

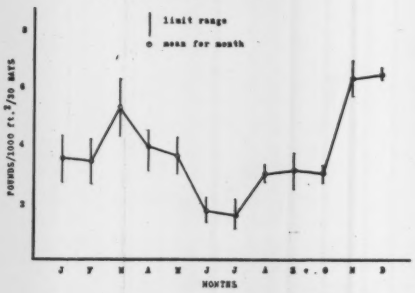

Fig. 1. Chart Showing Use of Limits in Analyzing Trends.

TABLE III
t Values for Significance at the 5% Level

No. of Samples	3	4	5	6	7	8	9	10	11
Value of t	13	4.3	3.2	2.8	2.6	2.4	2.4	2.3	2.3
No. of Samples	12	13	14	15	16	17	18	19	20
Value of t	2.2	2.2	2.2	2.2	2.1	2.1	2.1	2.1	2.1
No. of Samples	21	22	23	24	25	all higher values			
Value of t	2.1	2.1	2.1	2.1	2.1	2.0			

The Committee on Air Pollution Measurements.

W. R. Bradley, R. Chass, L. V. Cralley, C. W. Gruber, S. R. Hall, J. W. Hammond, H. C. Johnson, B. Linsky, A. Peterson, J. C. Radcliffe, J. H. Smith, E. P. Wheeler

H. M. Chapman, Chrm.

Comments by the Air Pollution Measurement Committee in answer to critical review by members of the Technical Coordinating Committee.

Control Station

The difficulty in locating a Control Station is considerable. The prevailing wind in one month is not necessarily the prevailing wind in another month, and the benefits provided at one time may be cancelled out in the following month. The Control Station is permanent when once selected. Locating a Control Station up-wind of the prevailing wind is of secondary importance to selecting a site which is free of local or regional influence. Therefore, I would not like to see the prevailing wind made a major issue. In our location in the Lehigh Valley, if we were to locate up-wind (prevailing), we would be influenced by the cement industry, and the use of the Control Station as a relative measure would be in doubt. I have tried to circumvent this situation with the wording you will find on Page 5.

Anti-Freeze

There is much to be said for use of glycerine as an anti-freeze, but its disadvantages are also tremendous. The author of this comment has argued very well for glycerine, but I think the crux of the problem is contained in his statement in which he says, "In recovering the insoluble portion of the sample which is roughly 99.9% of the total sample, we utilize Gooch crucibles with perforated bottoms and an asbestos fibre mat which is built up in the laboratory in a very simple manner. We find the filtration proceeds quite rapidly in fact much more rapidly than would be the case if thin alundum crucibles of medium porosity were uitilzed."

By this method, which utilizes evaporation of the liquid portion to a particular density followed by filtration of precipitated solids, I presume he does find that the insoluble fraction is 99.9% of the total. However, we know that the insoluble portion of most dust fall samples is more like 85% and sometimes only 70%, and it is reported in England that their samples often are only 40% of the total. I can only say that the remainder, which is the water-soluble fraction, must be lost when you are using glycerine. I think this is an important fraction, and the method of analysis should allow for its recovery. For that reason, we selected iso-propyl alcohol even though it lacks the permanence of glycerine.

Unit of Dust Fall

Considerable time was spent within the committee on the subject of this unit, and I believe we can say that it is the only one we like. The unit which we selected was considered to have the most meaning for the public. The public is aware of pounds, and the thousand square feet is roughly the size of the average dwelling, and so we expected it to have greater feeling than the old unit of tons per square mile per month. We did not like to use grains since the average person is not sure how much a grain represents.

Statistics

My remarks under **Reliability of a Mean** will take care of the situation at present, and I strongly recommend that this suffice for now. While I appreciate the usefulness of the "f" test, that is just one of several tests which might be applied. I am trying to hold down the complexity of the mathematics involved. The method originally outlined is similiar to the one used by the Manufacturing Chemists Association and also at Kettering Labs, and I feel we can have confidence in it.

Harlow M. Chapman, *Chairman*

Tailoring the Air-Pollution Ordinance

(continued from page 152)

community of certain categories of industry known collectively as "noxious trades". If every community sought to foist these industries on its neighbors, there would be no place in the county where several necessary local services could be performed. It is obviously no solution to force all such industries to form an uncontrolled ring of stench and fume just over the city, village or town line. The natural growth of all urban areas is forcing residents to and beyond their corporate limits, thereby creating enclaves of pollution sources in their midst.

Some zoning ordinances prohibit neither all industry nor designated noxious trades, but instead set up various categories of industrial zones, some in which the noxious trades may settle, and others which categorically exclude any land use which will cause objectionable smoke, soot, odors, fume, dust, or other designated forms of air pollution.

Zoning Precautions

The last, while a distinct improvement over the other types described, has several pitfalls, the most obvious of which is that such ordinances almost never incorporate standards against which to judge the emission. Other difficulties arise when an industry changes its processes from nonobjectionable to objectionable, and out of the presence of objectionable industry predating the adoption of the zoning ordinance.

Where an industrial zone is created in which offensive trades may legally operate, it should be carefully insulated from residential zones by either buffer non-air-pollution-producing industrial zones, by commercial zones, or by agricultural and grazing zones, in none of which should new residential construction be permitted.

These shortcomings of zoning ordinances point up the need for the careful coordination of the air-pollution-control ordinance and the zoning ordinance to make them jointly equal to the twin tasks of coping with objectionable emissions and of preventing the addition of objectionable sources to new areas of the community.

Among the points in favor of the use of the zoning ordinance as an air-pollution-control device is the fact that in so verbose a document as a zoning ordinance, a fairly lengthy section on air-pollution-control does not seem out of place or proportion; whereas these same air-pollution-control provisions standing by themselves sometimes seem out of proportion to the size of the community. Another point is that the community too small to justify the creation of an air-pollution-control board may be large enough to justify a zoning board which meets regularly, has counsel and secretary, and attracts the foremost citizens as members. Therefore, if the zoning board can also be used as an air-pollution-control board, with powers and duties common to such board (specifically, those of setting emission standards, of hearing appeals, and granting variations) the smaller community gains a very valuable enforcement tool at minimum extra cost.

New York State Data

It is recognized that only a small percentage of communities currently have zoning ordinances. Yet in one state — New York[2] — it was found (Table IV) that the ratio of communities seeking control of air-pollution by zoning

(continued on page 182)

(2) Data collected when the author was Chief, Engineering Unit, Division of Industrial Hygiene, New York State Department of Labor.

TABLE IV
Air-Pollution-Control Legislation in New York State Communities of Between 1000 and 25,000 Population

Population in Thousands	Number of Communities		
	In Study	Control of Air Pollution by	
		Air Pollution Ordinance	Zoning Ordinance
10 - 25	57	21	10
5 - 10	97	21	17
3 - 5	116	11	10
1 - 3	216	8	14
Total	486	61	51

Tailoring the Air-Pollution Ordinance

(continued from page 181)

ordinance to those doing so by means of specific ordinance provisions increases as the size of the community decreases. In the group of 33 New York State communities of over 5000 population which restrict air-pollution by means of zoning ordinances, 23 contain the industrial zone-type restriction, and 28 the offensive emission-type restriction. The majority of the ordinances restrict on both bases.

Conclusion

Zoning ordinances have not proven to be by themselves sufficient legislation for air-pollution control. They are ineffective against residential, mobile, and portable sources. If a community must choose between the 2 forms of ordinance, an air-pollution-control ordinance alone is preferable to a zoning ordinance alone. However, the small community gets the best legislative package by adopting both an air-pollution-control ordinance and a zoning ordinance, each of which is tailored to supplement and complement the other.

Air Pollution Damage to Vegetation

(continued from page 150)

bleached or ivory colored areas, as in cereals and alfalfa.

In chlorotic injury the affected tissue is deficient in chlorophyll, but the extent of pheophytin conversion is not high, and such leaves may recover their normal functions if plasmolysis has not taken place, i.e., the cells retain their normal water content. Repeated or prolonged exposure to sulfur dioxide below the threshhold injurious concentration has no appreciable effect on the chlorophyll content of leaves, as shown by sample specimens from the inner and intermediate fume zones of a smelter area. Katz[6], Thomas,[17] and others [18,23] have shown that sulfur dioxide absorption by leaves in subtoxic amounts produces no deleterious influence on photosynthesis and rate of growth. The gas is stored in the tissue largely as sulfate, and this may reach a value of 3 to 5 times the quantity normally present before it becomes toxic.

Deposits on leaves and in stomata from smoke and other aerosol contaminants in an urban environment may cause little, if any, discoloration but can result in a reduction in the normal chlorophyll level.

(6) See footnote 6, page 145
(17) See footnote 17, page 148
(18) See footnote 18, page 145
(23) See footnote 23, page 145

Electroprecipitator Studies

(continued from page 141)

tant from the collection-electrode surface in all directions at all points, whereas such is not the case for a discharge electrode located between two parallel collecting-electrode plates of the dry-duct unit.

2. The uniform distribution of the gas flow among the few individual pipes in a small unit cannot be approached in a larger unit containing a multiplicity of cleaning ducts.

3. In a large unit, it is impossible to get all the many parallel-connected discharge electrodes as perfectly positioned with respect to the collecting electrodes, as is possible in a small unit containing only a few electrodes. For this reason, the tendency toward arcing is greater in a large unit, and lower voltages must therefore be employed with some sacrifice in cleaning efficiency.

The importance of careful discharge-electrode spacing was confirmed in the tests with the small pipe-type unit. In the first tests made with the unit, the discharge electrodes had not been perfectly aligned, and the cleaning efficiencies were about 3% lower than those obtained after proper alignment.

Just as the required retention times for the smaller pipe-type unit were considerably less than those for the larger pilot plate-type unit, so were the required retentions for the pilot plate-type unit considerably less than those required for a full-scale installation. This emphasizes the fact that the smaller the unit, the better its performance, so that it is important not to consider small-scale results as directly indicative of the performance to be expected of a large commercial installation.

Although the experiments with both the pipe-type and dry-plate precipitator yielded a considerable amount of valuable information concerning the electrostatic cleaning of open-hearth gas, especially with respect to scaling up precipitator size, they did not, as was hoped, indicate any promise of substantially reducing the required size or the cost of precipitators for a given gas-cleaning job. Accordingly, tests are now being conducted to determine the possibility of employing other types of cleaners such as a high-energy wet scrubber (orifice or venturi scrubber) for the cleaning of open-hearth gas.

We are naturally hopeful that current research will yield solutions to the problem of open-hearth gas-cleaning at a reasonable cost, so that we may soon put the cleaning of open-hearth gas in the same category as the cleaning of blast-furnace gas, the latter being "a well established art currently being practiced on a huge scale."

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Transport of Atomic Debris

(Continued from page 156)

eastern states on the following day. By June 4, almost the entire country was experiencing fallout from this burst.

Summary

Collections of radioactive debris were made daily at 120 Weather Bureau stations throughout the United States during the atomic test series in Nevada in the Spring of 1952. The measuring techniques employed and the meteorological factors involved in the transport and deposition of debris are discussed. Several examples of the relation of computed meteorological trajectories to actual observations of debris are given.

Acknowledgments

The work reported on here was done under the direction of Dr. L. Machta, Chief of the Special Projects Section of the Weather Bureau. The radiological data were provided by the Health and Safety Division of the New York Operations Office of the Atomic Energy Commission, Merril Eisenbud, Chief. Many helpful suggestions were received from the author's colleagues, including H. L. Hamilton, Jr., L. F. Hubert, K. M. Nagler and F. Pooler, Jr. The laborious and painstaking plotting of data and preparation of finished drawings was done by the staff of the Special Projects Section.

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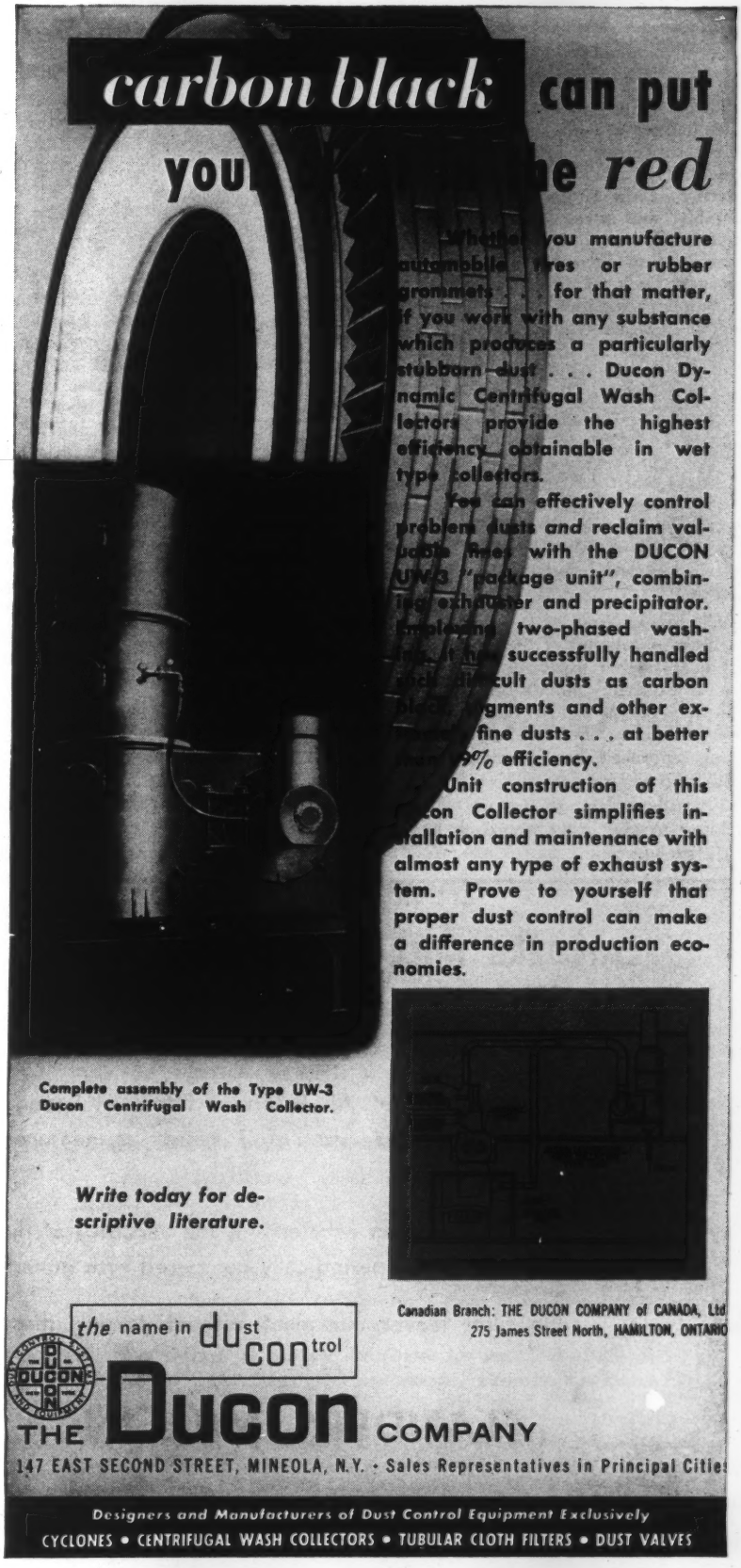
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Catalysis

(continued from page 175)

bon. Once catalytic oxidation has been initiated, if the concentration of flammable matter is such that a substantial temperature rise occurs on passage through the catalyst, the surface temperature of the latter is increased considerably, and substantially lower temperatures in the entering gas stream are tolerable, thus decreasing the preheating demands. Such conditions are favorable to complete oxidation with a minimum amount of contact time. When the concentration of the flammable matter is low, so that the temperature increment on catalysis is small (in the range of 50°F. or less) the residual concentration approaches zero as an asymptote when plotted against contact time; and due allowance must be made for this fact in the design of systems in order that acceptable concentrations in the exhaust may be reached. This is particularly true in the case of substances difficult to oxidize.

We believe it is apparent that with intelligent treatment of the practical and technical factors involved, the application of catalytic combustion in the air-pollution-control field will continue to grow. While it requires a type of engineering approach not common to this field, a broad segment of the over-all air-pollution problem shows no sign of yielding to any other approach known at the present time.

Is the Mass Self-Cleaning?

(continued from page 143)

the surface of the earth to represent a significant part of it, that he begins to make significant inroads on natural resources, including his air supply.

To return to our analogy between air and water pollution problems, it is customary to regard oxidative processes in water as a major element in self-purification. The picture is by no means so clear with respect to air. In the Los Angeles area, as a result of the pioneer researches of Dr. Haagen-Smit, it has been demonstrated that a relatively large amount of some oxidant, probably ozone, is produced in the atmosphere through a process activated by radiations from the sun. The particular reaction which is most suspect in Los Angeles is one involving the oxygen of the atmosphere, hydrocarbons and nitrous oxide. Exposure of mixtures of hydrocarbon and nitrous oxide to appropriate wave lengths of ultraviolet light have resulted in formation of ozone in quantities comparable with those occurring during daylight hours in the city, and ultraviolet irradiation of night air has also been shown to produce ozone and smog. This type of interaction is currently considered to be a principal source of the eye irritants and plant damaging substances which are of such frequent occurrence in southern California cities.

While there is apparently some doubt as to the extent to which this particular reaction occurs in other cities, especially in those in which there is a lesser amount of solar energy available, the general importance of the observation lies in the fact that a great many types of photo-activated reactions are possible under conditions of great dilution of gases and solids. There is no assurance that the compounds produced by reaction under these circumstances will be *less* objectionable than the original participants in the reaction. Consequently, it is to be doubted that oxidative phenomena can be regarded as a part of a self-purifying mechansim so far as air is concerned. Nevertheless, elucidation of the kinds of photochemical processes which occur in the atmosphere, and especially of the critical concentrations required by them may, in the future, lead to specific methods for control of irritating or poisonous substances. For example, if the production of eye irritating materials is indeed the result of interaction of hydrocarbons with naturally produced ozone at a particular level of hydrocarbons, then it should be possible to control the concentration of hydrocarbon within limits which will not permit the reaction. Thus, without making an effort to prevent the production of all effluents, industrial or domestic, it may be possible to effectively eliminate the nuisance. I am not advo-

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cating that such a procedure will prove feasible in any particular case, but rather, offering this as an illustration of a principle of control for community atmospheres, which may ultimately be practical.

Conclusions

To return to the general thesis of our question—Is the Mass Self-Cleaning? The answer is obviously "yes." Were it not so, we would already be overburdened with solids, gases and liquid droplets, and life would not be tolerable. In answer to the corollary question — how much of the waste products of man's activities can the air available to us accommodate — we cannot be so definite. We can, in any local situation, take advantage of detailed knowledge of the local patterns of stream flow, stratification and stagnation to avoid the build-up of offensive or dangerous concentrations of specific substances. This should be possible through the same type of procedure that is used in calculation of the capacity of a stream for the reception of wastes. It will involve estimation of the amount of air available for dilution of effluents in relation to the amount of effluents to be discharged. Where there is no stream flow, there will obviously be a minimal capacity for the acceptance of wastes.

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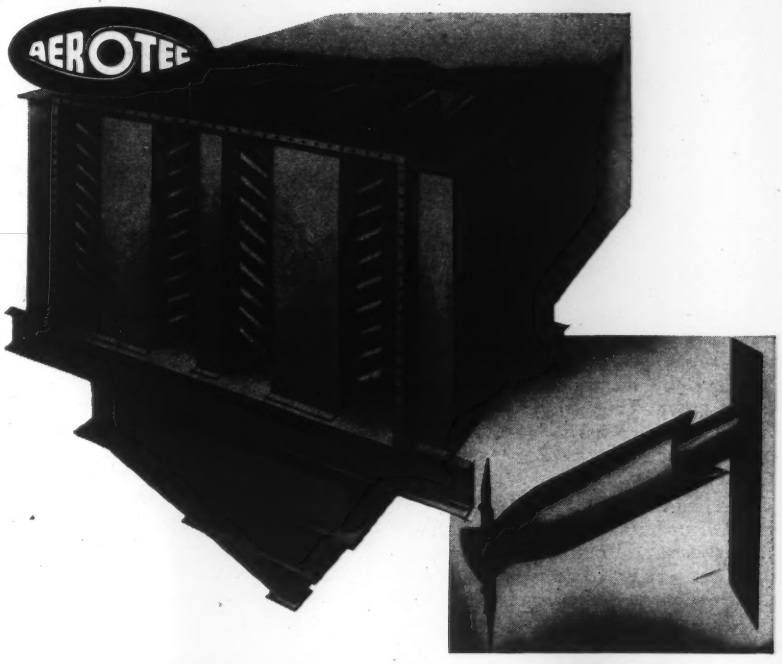
CORRECTION

Correction of Paper Entitled "Flame Photographs of Light-Load Combustion Point The Way to Reduction of Hydrocarbon in Exhaust Gas" by J. T. Wentworth and W. A. Daniel.

The vertical scale of Fig. 10 should go from 0% to 50% — not from 0% to 100%.

The final equation on page 102 should read

$$f = \frac{[CO_2]_m \ (mw_e)}{[CO_2]_m \ (mw_e) + ([CO_2]_e - [CO_2]_m) \ \frac{1}{\left(\frac{1 \cdot Z}{100}\right)(mw_e)}}$$



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Visual Clarity

(continued from page 172)

rings adjust to normal variations and changes in the diameter of the wool felt.

The cleaning rings are mounted in groups of 4 sets in a single carriage, 1 carriage per section. The drive motor on each unit serves to move all the carriages over the length of the filter elements in all 3 sections on that unit. The drive utilizes a conventional motor reversing system. Carriages are maintained perfectly level by means of a novel cable leveling system (Fig. 8). Level position of the carriage is important to assure proper contact of cleaning rings and filter elements.

The frequency and duration of the periods of operation of the cleaning system is controlled by a pressure switch. When the pressure drop across the collector reaches a preset level, the ring-traversing drive mechanism and the cleaning-air blower are energized automatically. When the action of the reverse jet restores the porosity of the felt, the pressure drop decreases and when it reaches a preset lower value, the cleaning system is automatically shut off.

This control makes the system completely automatic and is a great convenience, particularly when frequent plant shut-downs occur. It also makes for longer life for both filter elements and equipment mechanism, and it results in providing highest possible dust-retention efficiency at all times. The full advantages of pressure-switch control are obtainable only because of the special features that are unique to this form of cleaning system. In other forms of fabric collectors, the portion to be cleaned is usually put out of service during the cleaning period. In contrast to this, when a filter element is cleaned by reverse jet it is necessary that the element be in service and inflated to permit proper contact of the element with the cleaning ring.

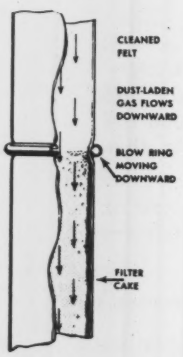


Fig. 6

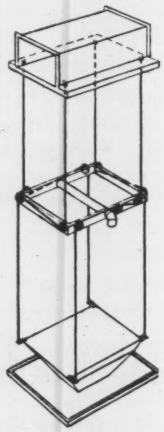


Fig. 8

By maintaining the preset limits fairly close (as is normally done) the resistance of the filter and the flow of gas through the system vary only slightly, with the result that there is no interference with the operation of the kiln. This feature is referred to as automatic porosity control.

Other Applications

In the adaptation of cloth collectors to a new application, many problems suggest themselves:

Would unburned oil droplets be carried through the system and deposit on the filter element?

Would the controls react fast enough to flashes of temperatures?

Would gas temperature drop below the dew point?

What other factors must be considered?

It is now possible to clear away these doubts by stating that on this job, installation and operation showed no serious difficulties. More than that, it paved the way for adaptation of this equipment to other asphalt-preparation plants. This has become possible as a result of a parallel development in filter materials. Only recently has a synthetic felt been made available for use in this type of equipment that will withstand 270°F.

Since the plants are shut down frequently during the day, some provision must be made to avoid the difficulties that would be caused by the gas temperatures falling below the dew point. It has been proposed(1) that a small burner (or the existing burner operated at reduced capacity) maintain the system temperature above the dew point during the many temporary plant shut downs. This would have the dual purpose of assuring dry filter elements and would eliminate the need to vent dust-laden gas to atmosphere during the preheat period that would otherwise precede a start-up.

With the experience gained on this installation and the other developments and suggestions discussed above, it is possible to adapt portions of the system used on this job to asphalt plants that operate in the more usual manner with the kiln being fed wet rock and sand and where the dew point of the gas is in the 150°F. to 160°F. range. Normally the temperature of the gas reaching the collector in such a plant varies from 200°F. to 325°F. For those plants where the temperature at the collector was under 270°F. no air dilution would be required. This is important because it would permit elimination of the air-dilution system and the dust collector could be sized for the actual gas volume without allowance for added dilution air. The Multiclone would be included or not, depending on the dust load of the particular plant. If low dust loads existed, the Multiclone could be eliminated. The auxiliary scrubber would no longer be required and would also be eliminated. The dampers and over-temperature control system would still be used, but since the gas would be vented to atmosphere during emergency conditions rather than to an auxiliary collector, a much simpler dampering system could be used.

For those plants where the temperature at the collector was over 270°F. it would still be necessary to retain the air-dilution system. All other equipment would be as described above. It is important to note that a much smaller volume of dilution air would be required to reduce temperatures from 300°F. to 270°F. rather than down to 180°F.

(1) Benjamin Linsky, Supervising Engineer, Bureau of Smoke Inspection and abatement, Detroit, Michigan. Verbal Communication.

Summary

The problem of collecting dust from kiln discharge gas in asphalt plants has been with us for a very long time. To the best of our knowledge no completely satisfactory method has been available previously to the operators of asphalt plants to obtain visual clarity in the stack discharge. Operators have, for the most part, been quite cooperative in applying dust-collecting equipment once the collectors have proven themselves effective and reasonably trouble-free. Lacking more suitable collectors, the operator has come to accept the high maintenance cost that is associated with the erosion and corrosion of his wet scrubber, as well as the high cost in many places of cleaning out his settling basins. There is every reason to believe that the knowledge gained at this plant and recent developments in filter fabrics will permit the application of reverse-jet collectors to any asphalt preparation plant, will result in stacks with no visible discharge, and will relieve the operator of the high maintenance cost and trouble of wet collectors.

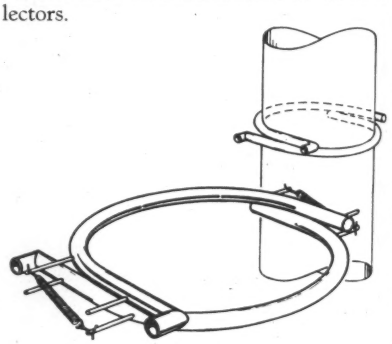


Fig. 7

Fume Problems in Electric Smelting

(continued from page 158)

Fig. 6. Gas Cleaning Plant for Closed FeMn Furnace (Porsgunn Elektor-metallurkiske A/S)

ments, each with 114-8¼ in. inner diameter steel pipes of 4.5 m. length. At 4 hour intervals one compartment is shut off and the pipes flushed with water for five minutes.

Data *	(for one furnace)
Fume collection efficiency:	98.5%
Power consumption:	
Electrostatic filter	35 kw
Fan	61 kw
Water pumps	67 kw
Total	163 kw
Water consumption:	
Scrubbing tower	96 m^3/h
Electrostatic filter	18 m^3/h
Total	114 m^3/h
Cost of installation:	$114,286
Cost of maintenance per year:	6,634

This plant has been in operation for several years and has given satisfactory performance.

Many closed furnaces for FeMn and carbide have been furnished with simple mechanical gas scrubbers of the disintegrator type. These robust machines precipitate the fumes and at the same time act as fans and give the desired gas pressure on the clean gas pipe line.

Fig. 6 shows a photograph from an installation in Porsgrunn, Norway, of a Buffalo scrubber connected to a 9,000 kva closed rotating hearth furnace for FeMn.

For closed furnaces the gas cleaning is no problem. The gas volume is small, dust concentration high, and despite the small particle size the fumes have good precipitation characteristics.

*All data are given with kind permission of Pechiney.

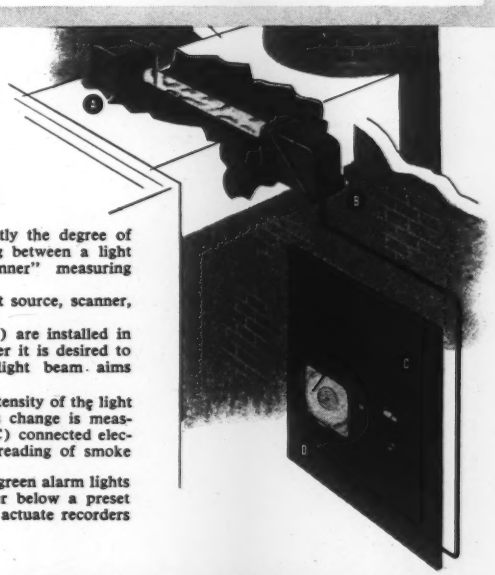
Look at Smoke through the Inspector's Eyes

Men who know most about the problem of air pollution agree that . . .

1. Everyone is anxious to avoid polluting the air because it means fuel waste as well as bad public relations.
2. Most offenders have the false idea that good fuel burning equipment, properly installed will not pollute the air. Most owners tend to forget that any slip-up in operating or maintenance can mean smoke from the best equipment.
3. Too few offenders remember that operators or custodians are *inside* . . . that a man at the boiler front can't know *what* is coming out of the stack, or *when* smoke occurs. That means smoke and fuel waste are undetected . . . and failure to quickly correct the condition back of it.
4. What every fuel burner needs is a really effective smoke indicator and alarm to signal that something needs attention in order to stop the pollution and fuel waste.

A majority of pollution and fuel burning experts also agree that the most effective system for detecting smoke, and warning the operator, carries the name FIREYE. Below is a brief description. Send for the new Bulletin which tells all about FIREYE System FE-3. You'll find the cost is so low that even the smallest apartment house can have it. Meets all smoke ordinances. WRITE FOR BULLETIN, NOW.

HOW fireye SYSTEM FE-3 WORKS



Fireye System FE-3 measures directly the degree of obscurity of smoke or haze passing between a light source and a photoelectric "scanner" measuring element.

Three simple basic elements—light source, scanner, and indicator—comprise the system.

Light source (A) and scanner (B) are installed in a breeching, stack, or duct—wherever it is desired to measure smoke density—so that light beam aims directly at scanner lens.

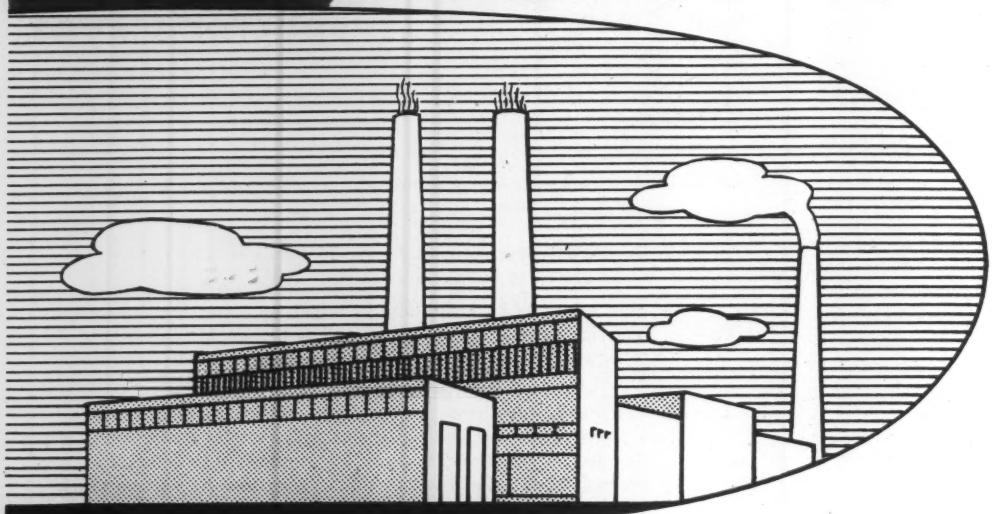
As smoke density increases, the intensity of the light the scanner receives decreases. This change is measured by Smoke Density Indicator (C) connected electrically to scanner, giving a direct reading of smoke density.

An extra visual check . . . red and green alarm lights tell when smoke density is above or below a preset level. Indicator can also be used to actuate recorders (D) and audible alarms.

E A fireye

COMBUSTION CONTROL DIVISION
ELECTRONICS CORPORATION OF AMERICA
Dept. C30-11, 718 Beacon St., Boston, Mass.

AIR POLLUTION...
AND INCINERATION ENGINEERING



Incineration can be carried on without causing air pollution from fly ash, cinders, smoke or odors. We make this statement based on our knowledge of and experience with incinerators during more than sixty years of service in the highly specialized field of incineration.

BUT, and this is an important BUT, the incineration unit must be designed to fit the problem. Seldom are two problems exactly alike, particularly in connection with incineration other than that of garbage and rubbish. For it is in these operations, such as listed below, that in the disposal of wastes one can run into real problems that require special engineering and experience:

WASTES OF HIGH HEAT CONTENT — plastics, sludges, gases, rubber, oils.

LARGE PIECES — reel heads, platens, lumber, auto bodies, animal carcasses.

CONTAMINATED WASTES — radio-active or bacteriological contamination of combustible wastes.

FUMES AND ODORS — catalytic or high temperature combustion.

ACID OR CAUSTIC CONDITIONS — factory waste materials other than hydrocarbons.

AUTOMATION — on charging, stoking and ash removal to a practical degree.

PREVENTION OF AIR POLLUTION — which may require complete temperature and combustion air control plus fly ash collectors, filters, washers.

LARGE CAPACITY — in municipalities, factories, refineries.

HIGH TEMPERATURE REQUIREMENTS — calcining, high ignition temperatures, efficiency in heat recovery.

Inquiries are invited. Our engineers are SPECIALISTS in Incineration We shall be very glad not only to discuss the application of incineration to any waste disposal or salvage problem confronting you, but design and construct the unit so there will be *no* pollution. Correct incineration can prevent air pollution.

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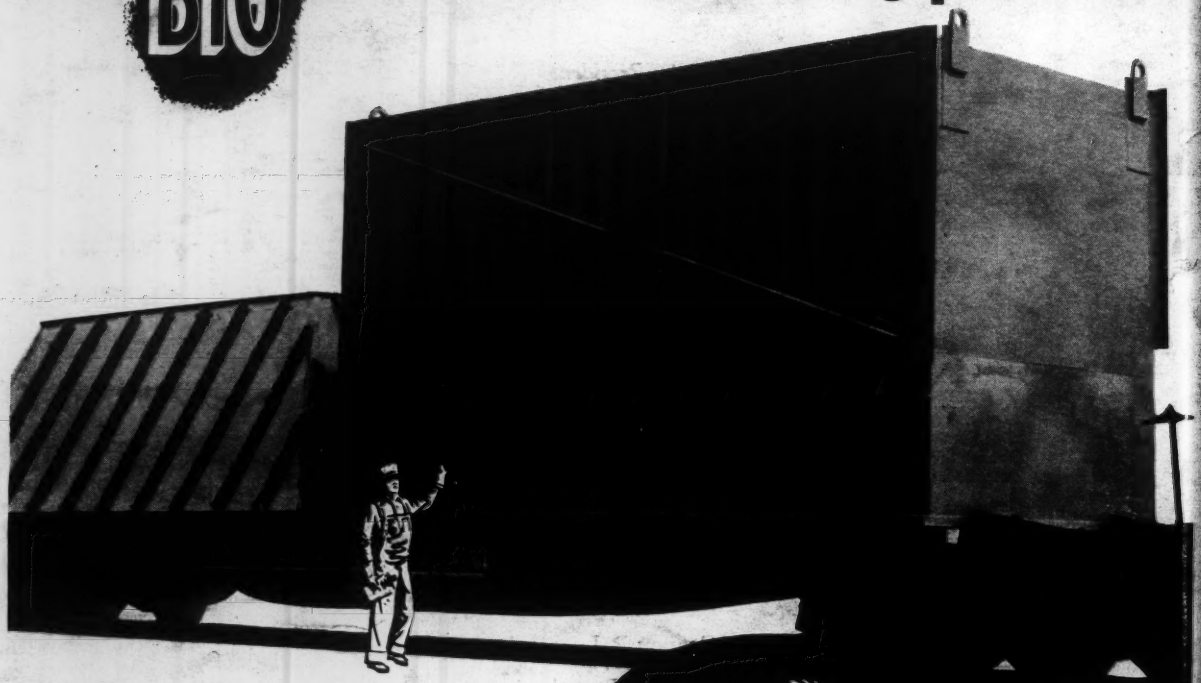
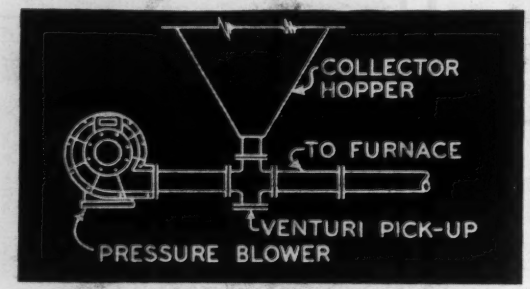
how BIG is your dust collecting problem?



SHOP ASSEMBLED COLLECTORS REQUIRE NO COSTLY FIELD ASSEMBLY . . . They are carefully assembled at the factory by experienced men using proper jigs and equipment to insure correct alignment of the tubes. Maximum collection efficiency is assured, as well as *lower installation expense.* WHIRLEX shop assembled collectors need only to be bolted into place.



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For plants with boiler HP capacities in the hundreds to larger boiler plants with capacities up to 1,000,000 lbs. of steam per hour, WHIRLEX completely shop assembled units are your most dependable answer.

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